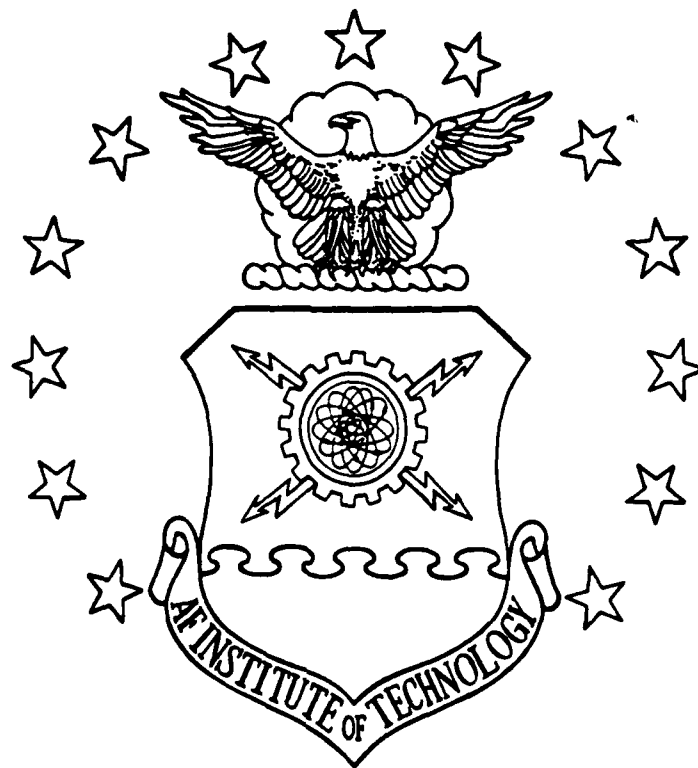


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ASSESSING POTENTIAL BENEFITS  
FOR  
SERVICE/REPAIR AND RETRIEVAL  
OF SATELLITES: A PILOT  
DECISION ANALYSIS

THESIS

Michael A. Del Pinto  
Major, USAF  
AFIT/GSO/MA/88-D1

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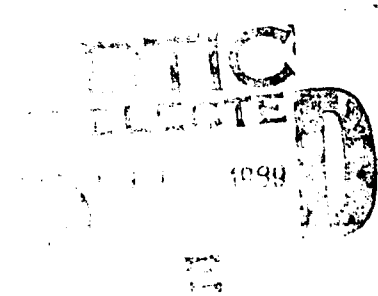
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THESIS

Presented to the Faculty of the School of Engineering  
of the Air Force Institute of Technology

Air University

In Partial Fulfillment of the  
Requirements for the Degree of  
Master of Science in Space Operations

Michael A. Del Pinto, B.S.

Major, USAF

December 1988

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Abstract

The Air Force is considering adopting an on-orbit service/repair strategy for some of its satellites. The decision must be made on a program-by-program basis. A pilot decision analysis was conducted to demonstrate the application of the decision analysis methodology to the decision. A pilot model, using influence diagrams, was developed for a general satellite program. Several spreadsheet programs were constructed for use with the pilot model. A scenario was presented involving a hypothetical communications satellite program. The pilot model was applied to the program and an initial decision analysis was performed. The salient aspects of the analysis were presented to exhibit the advantages of decision analysis as a methodology for structuring and analyzing the decision. The example analysis revealed the strongpoints of the methodology when applied to the case of a decision maker faced with a decision involving uncertainty, complexity, and value preferences. The pilot model and analysis serve as a foundation upon which further application of the decision analysis technique to the on-orbit service/repair decision can build.

# ASSESSING POTENTIAL BENEFITS FOR SERVICE/REPAIR AND RETRIEVAL OF SATELLITES: A PILOT DECISION ANALYSIS

## I. Introduction

### Problem Background

The U.S. military has become dependent on satellites to support its operations. Satellites are essential in such areas as communications, early warning, reconnaissance, and navigation. This dependence will only increase in the future. For example, the Air Force is proposing that several aircraft weather and strategic reconnaissance squadrons be deactivated in 1989 in favor of the satellite's demonstrated capability (7:169).

The cost associated with providing satellite assets is significant. The satellite scheduled to be launched on Discovery's November DOD mission reportedly cost half-a-billion dollars (17:25). Launch costs are also large. NASA charges upwards of 115 million dollars to the Air Force for a dedicated shuttle mission (16:36). Expendable launch vehicles are also an expensive means of transportation. NASA estimates a total launch cost of 157 million dollars (1987 dollars) for a Titan IV vehicle (16:34).

In the past, satellites have been single-sortie platforms. To get the most out of that sortie, efforts centered on extending a satellite's design life. But even then, they can be prematurely lost due to systems failures long before the end of their design life. Unlike the Air Force's aircraft, there was no possibility of performing maintenance to return them to

service. Also, unlike aircraft, satellites could not be serviced with replenishables such as fuel. Today, maintenance and servicing are possible to extend the single sortie or provide additional sorties for satellites.

The Soviet Union uses the Progress spacecraft to provide routine servicing for the Mir space station. NASA has flown several missions to retrieve disabled satellites. They have also repaired a scientific satellite on-orbit. The future holds additional prospects for improving U.S. capabilities to perform servicing and repair missions. The senior leadership of the Air Force has determined that these prospects should be examined for their potential benefits.

In a Air Force memorandum to the Vice Chief-of-Staff, then Under Secretary Aldridge indicated that "potential payoffs exist for repair, refueling or preventative maintenance of satellites" (2:1).

General Welch, then Vice Chief-of-Staff, followed this with a letter to all major commands:

Over the past decade our operational forces have become increasingly reliant on space systems to carry out critical functions which contribute to the security of our nation and its allies. This increased reliance has been accompanied by an evolving need to ensure that these assets are operationally available. Traditionally, this operational availability has been achieved by designs which emphasize reliability, system redundancy and spacecraft replacement. With the advent of the Space Transportation System and other technologies we should now assess an additional alternative for ensuring the operational availability of our space systems--spacecraft maintenance after launch (particularly preventative maintenance, refueling and repair) (27:1).

#### Problem Statement

The problem addressed in this thesis is to examine how the potential benefits of servicing/repair and/or retrieval of satellites to the Air Force can be determined. The costs and benefits, as well as the risks and

uncertainties involved, must be comprehensively considered in the examination of the problem.

#### Purpose of Study

The purpose of this study is to demonstrate the possible utility of decision analysis (DA) as a methodology for structuring and analyzing this problem.

#### Methodology

A pilot DA model was developed. Ideally, this is done interactively with the actual decision maker. For this pilot study, two Air Force officers provided the necessary inputs to construct the model. Major Jackson, HQSD/XR, provided the current studies the Air Force is using to analyze the problem. Major Sheridan, AFSC/XPS3, provided NASA documentation. Both officers discussed the issues by telephone or in person.

The pilot model provides understanding about the nature of the problem and the major factors bearing on the decision as to whether the Air Force should pursue the benefits of servicing/repair and/or retrieval for its satellites. It provides a "simplified decision model, a tentative preference structure, and a rough characterization of uncertainty" (6-13).

The graphical structure of the pilot model was then used to develop several spreadsheets for the model's application. The model's variables are elements of several spreadsheet programs. Each spreadsheet models a specific design strategy for a satellite program. They calculate the net present value of an alternative satellite design strategy compared to an expendable design strategy. The spreadsheets allow a direct comparison of net present value for a satellite program where different design strategies

could be employed. In the decision analysis context, the spreadsheets provide the value of an outcome defined by a combination of variables. The variables can then be altered to analyze their effects on the net present value of an alternative. In this way, the spreadsheets provide insight into the factors bearing on any satellite program that may seek to take advantage of the potential benefits of an alternative design strategy.

A hypothetical scenario was used to demonstrate the application of the model to a specific case. Major Sheridan served as the surrogate decision maker for this example. A pilot analysis of the case was then conducted and the results presented.

The pilot analysis presented is a result of one iteration of the decision analysis cycle. Information gathering was based upon existing studies and discussions with Majors Jackson and Sheridan. The deterministic phase resulted in the pilot model and spreadsheets. The application of the model to the hypothetical scenario completed the deterministic phase. The probabilistic and informational phases were completed within the context of the scenario. The decision phase was completed short of making an actual decision in the scenario. The decision maker was brought to the point of being ready to select alternative or seek further information.

#### Limitations

The pilot analysis was developed using a surrogate decision maker and current studies instead of the actual decision maker. Access to the decision maker and his designated experts would personalize the model. In this way, it would reflect the decision maker's values, preferences, and uncertainties and would focus his knowledge of the issues involved.

No classified information was used. Several classified studies have been conducted. These have analyzed the potential benefits for specific programs.

Decision analysis is a methodology for structuring and analyzing a problem dealing with decisions made under uncertainty. The pilot study is intended as a demonstration of decision analysis to this problem and is not prescriptive. The model and its spreadsheet representations are useful, outside the decision analysis context, for any comparison of value for a satellite program where different design strategies are being considered.

The Air Force has become increasingly dependent on its satellite resources. Servicing/repair or retrieval have been advocated as means of increasing the benefits derived from those resources. What is known about our capability to service/repair or retrieve satellites? What analyses have been done to explore the potential benefits? Chapter Two will provide background information on those two questions.



## II. Literature Review

### Introduction

The purpose of this literature review is to present background information on both the current and prospective capability to conduct on-orbit servicing/repair or retrieval of satellites. In addition, several studies dealing with the cost and benefit aspects of those capabilities are reviewed.

A framework using three general chronological categories is used to discuss the current and prospective capability. First is the current capability based on the shuttle. The second category, near-term, includes the capability offered by the space station in its early configuration. The last is based on a mature space station. These categories are necessarily vague because they are based on development and deployment schedules that are constantly changing. In general, near-term is the 1990's and the mature space station represents the post-2000 timeframe.

### Discussion of the Literature

Current Capability. The shuttle represents the current capability to conduct on-orbit repair or retrieval of satellites. For this reason, only satellites in low-earth orbit (LEO) are candidates. But within this restriction, the shuttle has several features that make it effective.

The remote manipulator system (RMS) is a mechanical arm that can extend from the payload bay of the shuttle. The RMS can be operated by a crew member remotely from the shuttle cabin or by an astronaut operating outside the shuttle. The RMS can be used to deploy or retrieve a satellite or as a work platform for astronauts operating near the shuttle (20:56-58).

The ability of an astronaut to conduct extravehicular activity (EVA) is another important aspect of the shuttle's capability.

The astronaut's greatest contributions are a product of his/her mental and physical attributes that no machine has been able to duplicate (26:2-19). Yet the astronaut depends on two vital pieces of equipment, the extravehicular mobility unit (EMU) and the manned maneuvering unit (MMU), to make those contributions. The EMU is a space suit and the associated support equipment. It provides life support and communications to the astronaut. The MMU is a powered backpack that provides controlled mobility within about 100 meters of the shuttle (20:59-61).

Most sources point to two shuttle missions (STS 41-C and STS 51-A) as examples of the current capability to perform repair or retrieval. The first involves the on-orbit repair of the Solar Maximum Mission (SMM) satellite and the second deals with the retrieval of the Westar VI and Palapa B-2 satellites.

The SMM satellite had been designed for on-orbit repair (10:49). It had been launched in 1980 but had suffered failures in four of seven scientific instruments (10:49). In 1984, astronauts operating outside the shuttle and using the remote manipulator system, repaired the satellite on-orbit using spares (20:56;28:583). The benefit of that mission was that SMM was restored for approximately one-tenth of its replacement cost (10:52). Another opportunity to rescue SMM will come in 1990. The anticipated benefit of the rescue is that for a 25 million dollar cost SMM can be saved versus a 250 million dollar price tag to replace it (25:34)

In contrast to the SMM satellite, neither Palapa or Westar had been designed to accommodate shuttle capabilities. Because there were no

attachment points for the RMS, both satellites were manhandled into the shuttle cargo bay and then returned to earth for repair (14:258-265).

These two missions, in addition to highlighting the shuttle's capabilities, point out the difference between on-orbit repair and retrieval. The cost of relaunching Palapa and Westar must be considered. In the SMM example the satellite was repaired on-orbit and returned to service. NASA has gone on to include the capability for repair or retrieval in several programs (Space Telescope, Landsat, and the Long Duration Exposure Facility) (10:49).

Near-Term Capability. While the shuttle has had a number of successes, it does have several limitations. The shuttle operates in the LEO regime and is unable to reach satellites in other orbits (28:585;19:573). It has a limited capacity for spares (the shuttle bay held two satellites that it deployed prior to retrieving Westar and Palapa) and no servicing capability (28:585;19:573;4:93). The orbital maneuvering vehicle (OMV) is being designed with these limitations in mind.

The OMV is basically a small tug and service vehicle to be carried in the shuttle. It will be remotely controlled and will give the shuttle access to a wider range of satellite orbits. In its basic configuration the OMV will be able to extend the shuttle's reach to orbits as high as 1500 miles. The addition of a transfer stage will enable it to reach geostationary orbits (GEO) (12:197;4:93). While the OMV partially redresses one shortcoming, the space station may be the answer to both.

The space station is intended to be in permanent LEO and continuously manned. The shuttle will serve as a logistics resupply vehicle and provide replacement crews (24:8). This continuous presence and regular resupply

address current shuttle limitations. The space station will have a much greater capacity to store spares and consumables as well as a larger resource base (more electrical power, computing power, etc.). In addition, it will be available for long-term repair should a satellite require it. The orbital transfer vehicle (OTV) will serve the same functions for the space station as the OMV does for the shuttle. In addition, basing the OTV with the space station gives the space station an on-demand capability (28:583;4:93).

Like the OMV, the OTV will be a remotely operated transfer and retrieval vehicle. It will operate from the space station and will be able to access all satellites regardless of orbit. This capability will be built-in, unlike the OMV's capability which requires an additional thruster stage (20:76-78). In summary, the near-term capability is characterized by the shuttle/OMV and space station/OTV teams. The mature space station era is characterized by an evolution in the hardware capabilities.

Mature Capability. An evolving capability is planned for the elements of the established space infrastructure. Planned improvements are in store for the space station, OMV, and OTV.

As the space station matures, the shuttle will assume a secondary role in repair/servicing and retrieval of satellites. It will probably be used in contingency situations such as an emergency resupply or if the station is unavailable for whatever reason. Another case would be if the troubled satellite happened to be conveniently located near a planned shuttle orbit (4:95). With this in mind, only the OMV will have additional modifications in the shuttle/OMV team. NASA plans on fielding an improved remote manipulator arm for increased dexterity and adding the ability to transfer

propellants to the OMV (12:198). The OTV will have the same improvements but will undergo a more dramatic change.

NASA plans to convert the OTV into both a manned and unmanned version. Both versions will have advanced propulsion systems and increased payload capacity (12:444;3:114). To accommodate the OTV's increased capability, several changes are envisioned for the space station.

In the post-2000 era the space station will add a docking unit. This will provide the capability to perform repairs "indoors" in a shirtsleeve environment. It will also allow assembly and checkout of satellites at the space station prior to transfer to orbit. The space station structure will also be expanded to provide additional storage capacity for spares, repair equipment, propellants, etc. (5:105;13:210).

The evolving capability for repair/servicing and retrieval of satellites rests on the notion that the benefits of this capability outweigh the costs.

Benefit/Cost Studies. Four studies were reviewed (references 8, 9, 15, 16, 22 and 23) that were either partially or totally dedicated to the cost/benefit question. Three perspectives were evident in the studies. The Lockheed study looked at both NASA and DOD satellite programs. TRW and SAIC/Tecolote concentrated on DOD programs. The last, the NASA study, was intended for commercial companies to aid in gauging the cost and benefit of servicing/repair or retrieval for their own commercial satellites. The first three studies can be reviewed together.

The first three studies take a similar approach to the problem. They define a series of key parameters to be used in their analyses. These parameters are uniform across the studies when general categories are

considered. They only differ in the degree of detail to which one parameter is further broken down.

The parameters are then used in various computer models to arrive at the possible savings. The parameters are varied through a range of values to determine the sensitivity of the savings benefit to each parameter. The studies use the sensitivity results to define a series of "break" points for the parameters. These break points determine characteristics which either favor or disfavor repair/servicing or retrieval over replacement of satellites. For example, low satellite cost is a disfavor (15:3SAMS50).

The parameters deal strictly with the "hard costs" associated with the question. They are hard costs in the sense that they would be actual budget items in any program. These include such things as satellite cost, NASA charges, and launch vehicle cost. The intangible costs and policy issues are descriptively addressed to some degree. The TRW study, for instance, includes issues such as technical feasibility and the requirement for a national decision as to whether the investment should be made (22:41). While all of the studies deal with actual costs, how are these costs treated to arrive at a benefit?

The studies compare satellite programs across a program length. A comparison is made between completing the program with the current expendable strategy, replacement of satellites upon failure or the end of their design life, against a strategy that includes routine servicing and repair or retrieval. The difference of the cash flows defines the benefit achieved. The specific method that defined the benefits is not self-evident in the studies. A limitation is the fact that the studies were done for a closed audience. This audience may be privy to all the

assumptions and computations, but an outsider only has a partial list.

With a closed audience in mind, it appears that the studies took a "here's our answer to the question you asked" approach.

One question in particular is important. The problem deals with a series of cash flows. To arrive at an overall benefit, some time-value-of-money factor must have been used. This was probably specified in the contract to the firms that performed the studies and known in house. Only the TRW study makes explicit mention of the discount rate used in its calculations. The NASA study took an entirely different approach.

The NASA study presents a series of worksheets for a commercial company to use. In addition, they provide a series of NASA charges for services and tables of cost data for such items as launch vehicles. The company is then led through the worksheets and can compute the anticipated cost of including service/repair or retrieval features into his satellite. He can then compare the life-cycle costs of this option against replacing the satellite at intervals.

Information on what our present and prospective capabilities to perform servicing/repair or retrieval and on several efforts to examine the cost/benefit question of those capabilities has been presented. The pilot DA model will now be developed.

### III. Model Development

#### Overview

The goal of any decision maker is to make a decision based on a thorough understanding of the problem. Making an informed decision in a complex problem fraught with uncertainty is a difficult undertaking. A decision maker must determine what factors bear on the problem, what is known about those factors, and how they are related. He must recognize the possible alternatives and payoffs. He must appreciate the risks involved in selecting an alternative. Only then can an informed decision be made. The process is one of decomposing a complex problem into its key elements, studying those elements, and then recombining them. Decision analysis (DA) provides a framework for doing just that. (6:23-38)

Influence diagrams and the underlying decision and probability trees are used to model the structure of the problem. Key variables, their relationships and their uncertainty are defined in this structure. (See Appendix A for more information on influence diagrams and how they are used in this model.) A systematic top-down approach is used in decomposition. A variable at one level is further decomposed only if the additional detail is required to decide between alternatives. The objective is to include enough detail to make a decision and not to precisely model reality. (1:1)

#### Decisions and Alternatives

A new satellite program can be a follow-on to an existing one (DSCS III replacing II) or it can represent a new capability (GPS). The normal DOD acquisition cycle is simplified by modeling the new program in two distinct phases--the R&D phase and the operational phase. Each phase is initiated



with a decision. These are the two critical decisions modeled.

The first decision is a choice of which design strategy to pursue in the research and development phase for a proposed satellite program. In this pilot study, four alternatives are considered. These distinguish four alternative methods of maintaining the desired number of satellites on-station. Other elements of satellite design are not considered. They are assumed to be constant across the alternatives. For example, if new optics are being developed for a satellite, they will be developed regardless of how the new satellite constellation is maintained. The decision variable R&D is used in the influence diagrams to represent this decision and its four alternatives.

The first alternative (EXP) is basically a "more of the same" approach. The design strategy will continue to rely on expendable satellites to meet mission requirements for the operational length of the program. Current design-life technology will be used. In the case of a follow-on program, new satellites will have the same lifetime as those they are replacing. For a new-capability program, current design-life technology is used.

The second alternative (R&R) is an extension of the first. The design strategy will continue to rely on expendable satellites but they will incorporate changes to increase the lifetime. Component improved reliability and/or redundancy will be pursued in the design.

The next alternative (RRR) is the retrieve, refurbish, and relaunch design strategy. The spacecraft will incorporate features that allow it to be retrieved to a location where it can be refurbished and then relaunched to its operational orbit.

The last alternative (S/R) is to service and/or repair the spacecraft while on-orbit. The satellite design must include features that will allow it to be serviced and/or repaired from another vehicle.

There are several permutations to these alternatives. For instance, a combination strategy could be pursued through a spacecraft design incorporating increased lifetime as well as service and/or repair features. Several strategies may, perhaps, be co-developed in the R&D phase as a hedge against failure in one design strategy. In keeping with the purpose of this pilot study, only the four defined alternatives are considered.

The second decision is whether or not to produce and deploy the satellite developed in the R&D phase. It is modeled by the decision variable PROD. Two simple alternatives exist and they are self-explanatory--a yes or a no alternative. The decision maker will have information available prior to making either of the decisions. In addition, each decision will result in an outcome.

#### Outcome and Value Variables

The information available to the decision maker prior to the R&D decision is modeled by the program definition variable (PROG DEF). This variable details the mission requirements pertaining to the problem. The outcome of the R&D decision is the variable R&D RESULTS. Later, these variables will be precisely defined by their respective system variables. The information in the PROG DEF and R&D RESULTS variables is available prior to the PROD decision as well. In addition, the decision maker will naturally know the result of the R&D decision.

The no alternative of the production decision, (PROD), results in an outcome where all funds spent to that point to develop the design strategy

are considered a loss. The yes alternative yields the outcome of a minimum schedule of events that will meet the program definition. With the case of the expendable satellite as an example, this schedule includes the minimum number of launchers and satellites, operations and support (O&S) costs, etc. necessary to keep a required satellite constellation operational for the length of the program. The minimum distinction is important. No allowance is made for an unscheduled need to replace a satellite. Satellite failures prior to the expected end of design life, launch failures, failed S/R missions or retrieval missions are some of the reasons additional events may be required. Unscheduled events represent an element of the risk associated with an alternative and will be incorporated through another variable.

The minimum schedule of events also defines a schedule of expenditures-- a cash flow. The decision maker is tasked with accomplishing a mission (program definition) through one of four design strategies. A satellite type must be deployed. The default alternative is to continue with the expendable design strategy. The direct value associated with the other three strategies in the operational phase (after the PROD decision) is derived from a comparison to the default alternative. The net difference between the cash flows ( $\Delta CF$ ) is the direct value of an alternative. Take the S/R alternative as an example. If its operational cash flow is 250 million dollars and the default strategy's cash flow is 750 million dollars, the direct value of the S/R alternative, in the operational phase, is a 500 million dollar cash flow. The outcome of the PROD decision is the direct value of an alternative's operational phase. The descriptions of

these outcome variables ( $RRR \Delta CF$ ,  $S/R \Delta CF$ , and  $R\&R \Delta CF$ ) will detail the direct value computations.

The variable R&D RESULTS has been described as the outcome of the R&D decision. An element of those results is the additional R&D cash flow, ( $R\&D \Delta CF$ ), associated with the alternative strategy compared to an expendable satellite strategy. It is computed just as in the operational phase. The alternatives' R&D cash flow is compared to the default alternative's. The resulting  $\Delta$ cash flow for an alternative in the R&D phase is a negative direct value. The assumption is that the alternatives will have a higher R&D cash flow than the default alternative ("you don't get something for nothing").

Another negative direct value is the additional infrastructure cost, prior to the operational phase, associated with an alternative strategy. As an element of R&D RESULTS, it is a catchall for any additional start-up costs for an alternative that would not be needed for the default alternative. Additional construction, manpower, and training are some examples of what may be included.

The value variable (V) represents the mathematical function that collects each of the elements of value. The result is the total value of each overall outcome for each alternative design strategy. Because of the comparative nature of the model, the overall value of the default alternative is zero. The default alternative is the baseline against which the other alternatives derive their value. A full description of the value variable will be given when the model is complete.

Figure 1 is the initial top-level influence diagram described thus far. Each variable is a node in the diagram. It is composed of the the decision

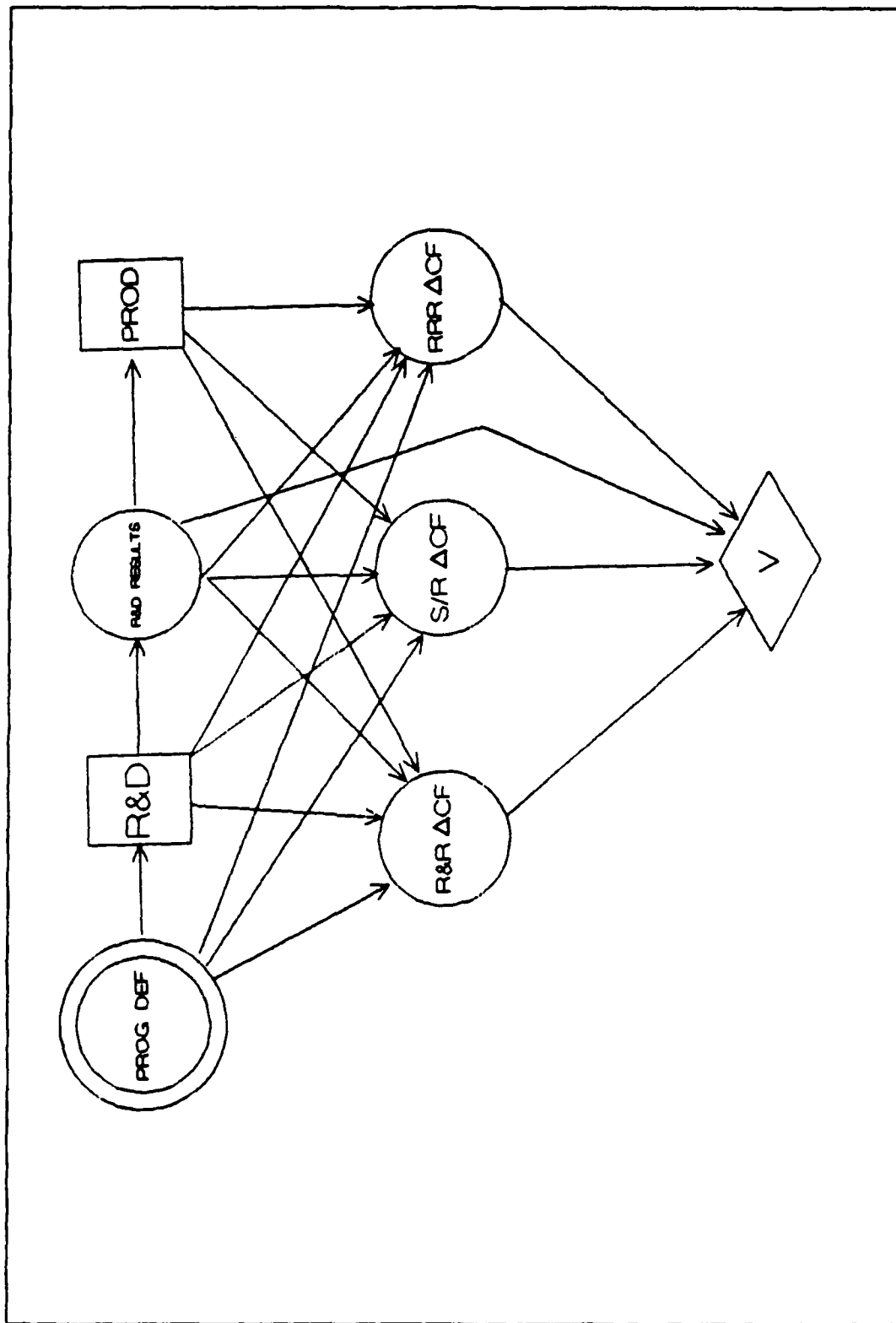


Figure 1. Initial Top-Level Influence Diagram

deterministic, and random variables described. When decomposed, the random variables will have their uncertainties explicitly modeled by their system variables. After decomposition, the random variables of Figure 1 will become deterministic variables. The definitions of several variables have only been alluded to and are actually described by further decomposition. The addition of several system variables provides the decomposition.

#### System Variables

There are seven important system variables detailing the program definition (PROG DEF). Figure 2 illustrates this expanded portion of the initial influence diagram.

Two variables divide the entire program into two phases. R&D LGTH is the anticipated length in years of the R&D phase of the program and the year the R&D phase will begin. OP LGTH is the length of the operational phase in years and the year of the first launch. It begins with the launch of the first satellite. The determination of the last year has several possibilities. Take the example of a single satellite program comparing a 5-year and a 7-year-design-life satellite. If the operational phase is defined as 15 years, three of either satellite would be required. However, the 7-year satellite would still have six years remaining on its design life. This is no problem if it is planned to switch to a new program at the 15-year point (the extra six years have no value). But if it is planned to delay the follow-on to take advantage of the six years, the value of the 7-year-satellite alternative must reflect this. In any case the same program length must be used for comparisons between alternatives and any decision maker assessments of additional value will be included in another variable.

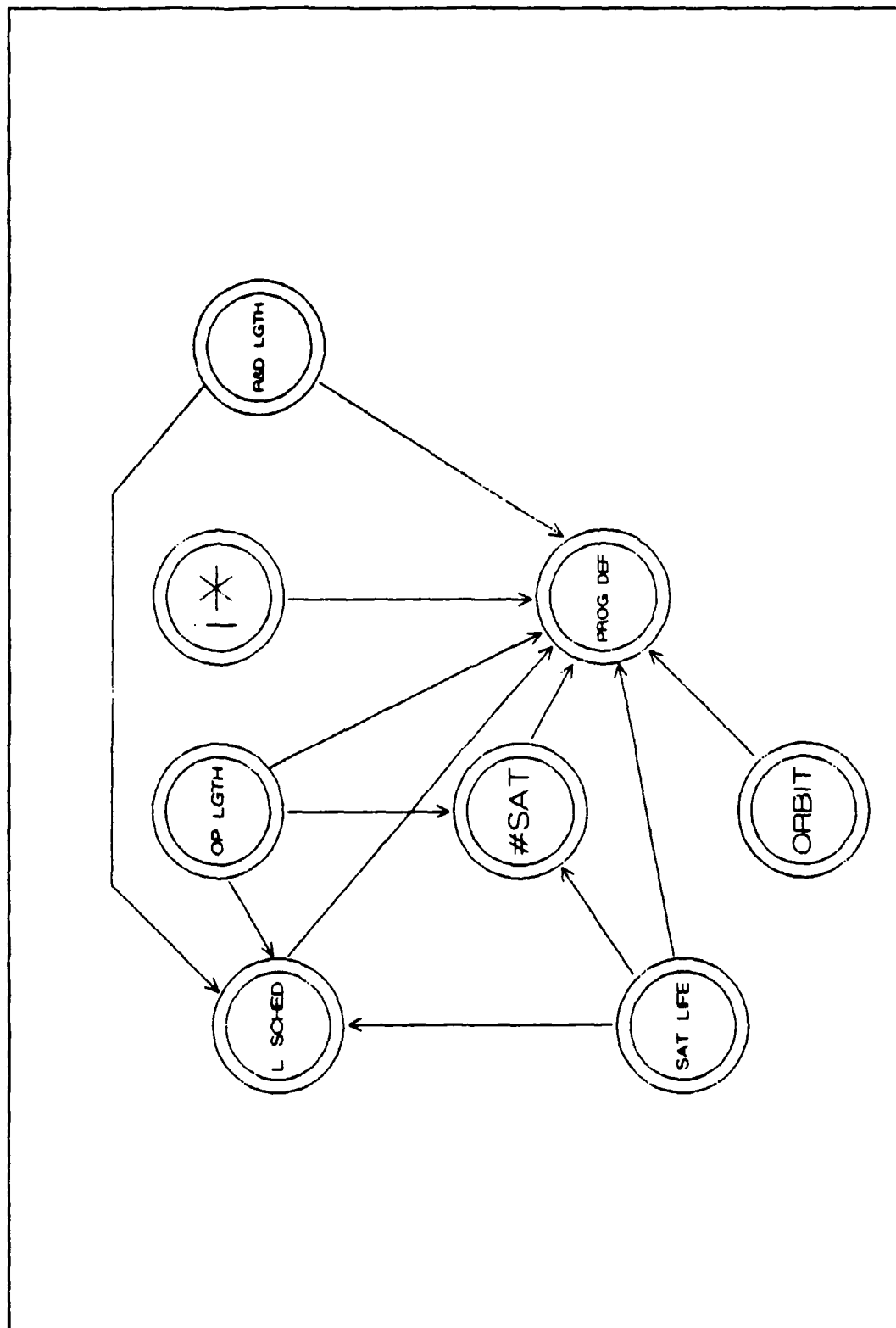


Figure 2. PROG DEF System Variables

The discount rate,  $i^*$ , is used to compute the net present value of the alternatives. The discount rate is usually predetermined by a higher authority and is simply a given for the analysis.

The variable ORBIT describes the locations of the constellation's satellites. This information is required to determine the necessary equipment that would be required to service/repair or retrieve a satellite.

The variable #SAT is the minimum number of satellites to maintain the required constellation (disregarding possible losses or spares) for the entire operational phase. This number is influenced by several other variables. The operational-phase length (OP LGTH) is certainly one. The design life (SAT LIFE) in years is another. The last two variables influence the planned schedule of launch years (L SCHED). L SCHED, SAT LIFE, and #SAT are dependent on the alternative selected.

The decomposition of R&D RESULTS is illustrated in Figure 3. The INFRA and R&D  $\Delta$ CF variables are the additional constant-year-dollar cash flows incurred in selecting an alternative as compared to the default alternative. The constant-year used in all cash flows is the year prior to beginning the R&D phase.

R&D success (R&D SCS) is the likelihood of successfully developing the alternative satellite's unique characteristics. The development of other features of the satellite, common to all alternatives, will have the same likelihood of success for all alternatives. Therefore it does not serve to differentiate the alternatives. The likelihood of successfully developing the servicing and repair features of a S/R spacecraft is an example of a unique aspect for an alternative. The RRR alternative is analagous. In the R&R alternative, it represents the actual satellite design life achieved.



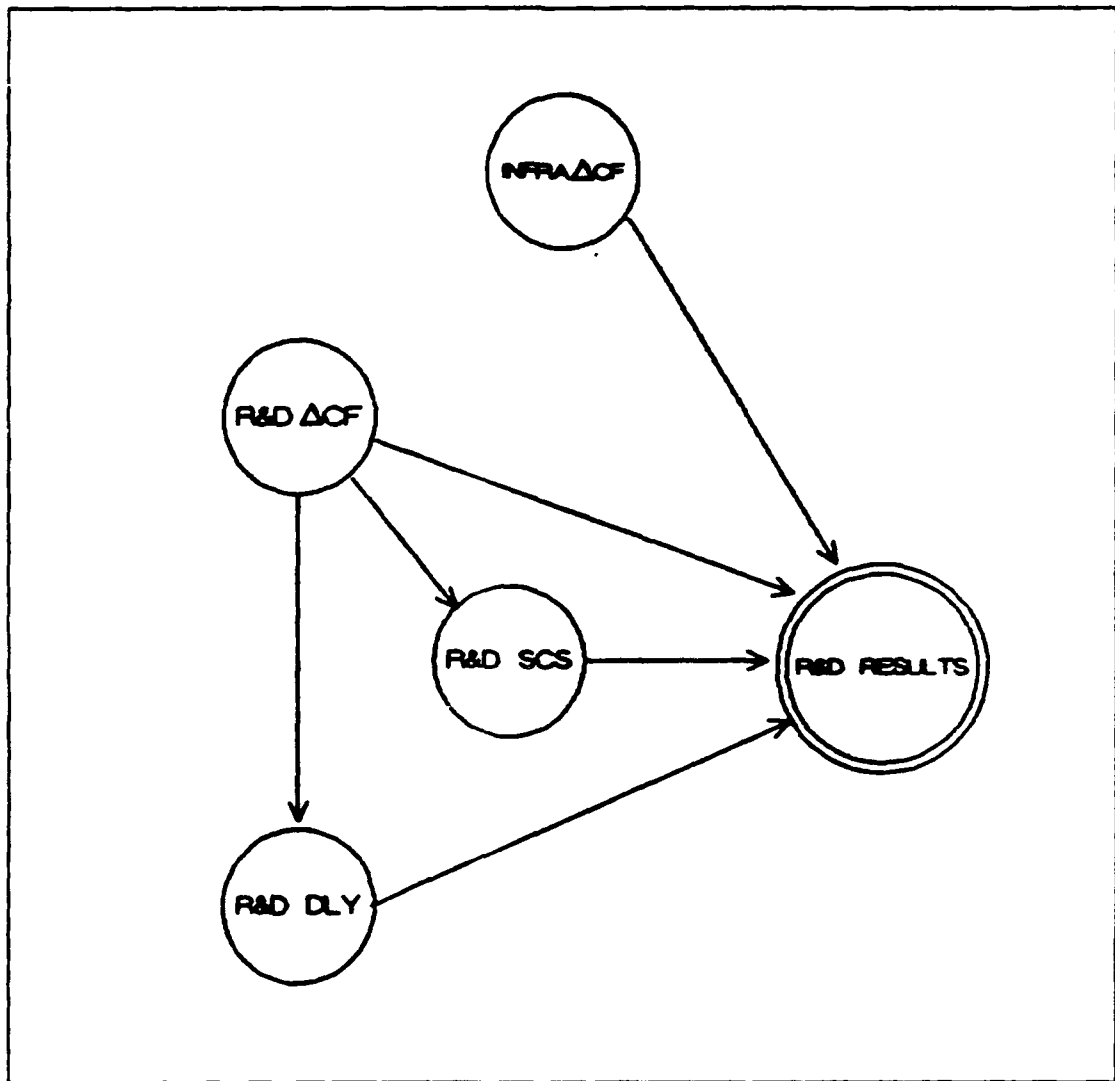


Figure 3. R&D RESULTS System Variables

One variable in this decomposition deals with the time aspect of the R&D phase results. The R&D delay, R&D DLY, is an estimate of the possible lengthening (in years) of an alternative's R&D phase over the anticipated length. The result would be a delay in initiating the operational phase of the program.

The three alternatives to the expendable-satellite strategy have very similar  $\Delta$ -cash-flow decompositions in the operational phase. The S/R  $\Delta$  cash flow and the unique variables in the other alternatives will be

defined. Again, all costs are constant-year dollars based on the year prior to initiating the R&D phase. Figure 4 is the S/R  $\Delta$ CF decomposition.

There are eight variables dealing with the cost of the S/R alternative. EXP COSTS are the costs of the expendable-satellite alternative. They serve as the baseline to calculate the costs associated with the S/R alternative. The  $\Delta$ LCH COST is the additional launch cost for an S/R satellite on a per satellite basis to account for multiple satellites on a single launch vehicle. The  $\Delta$ SAT COST is the additional cost of the S/R satellite. The additional annual O&S cost is modeled by the  $\Delta$ O&S COST variable. S/R MSN COST is the cost of the S/R mission. Finally, ORU COST is the cost of the ORUs and other replenishables, such as propellants, for each mission. It is expressed as a percentage of the S/R satellite cost.

The possible benefit of an S/R mission is computed in the S/R BEN. The benefit is a combination of cost avoided and cost incurred. An S/R mission takes the place of having to launch an expendable satellite to obtain the same satellite capability. The usual case is that a S/R mission will be launched near the end of a satellite's design life to return it to a "like new" status. Another possibility involves the satellite's overall reliability. A satellite's overall reliability decreases over time and a S/R mission may be used to return the satellite to its baseline reliability.(9:4-26-4-36) In either case, an expendable satellite would have to have been launched to obtain the same results in the default alternative. The cost avoided is the price of an expendable satellite and its launch costs. The cost incurred in the mission is the sum of the S/R mission cost and the ORU cost.

The S/R  $\Delta$ cash flow is a combination of the cash flows of the benefits

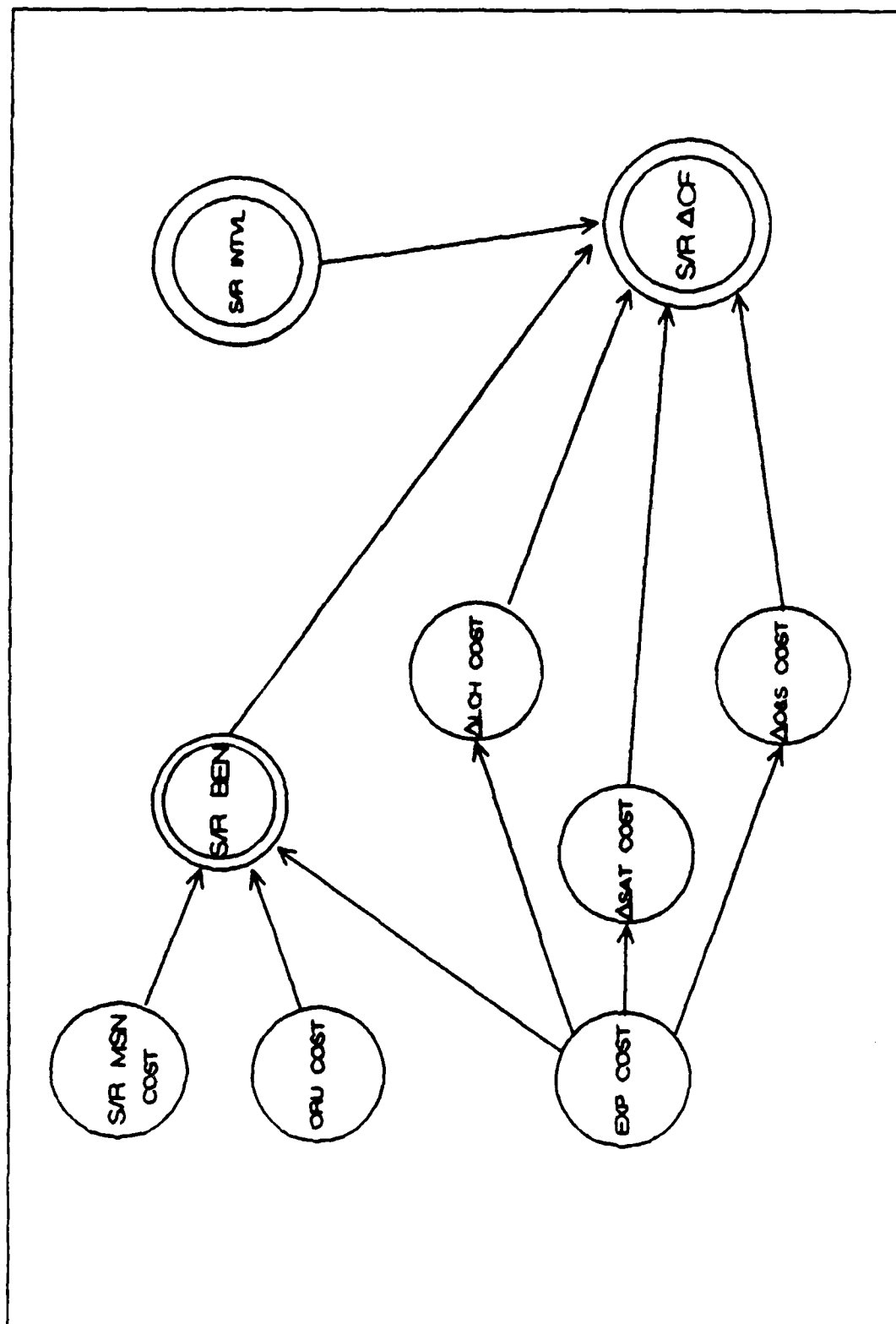


Figure 4. S/R Δ CF Decomposition

and the additional costs required to obtain those benefits. Remember, the default strategy has zero value by definition. If S/R  $\Delta$  CF is positive, the S/R alternative has met the operational-mission requirements at less cost. This is still without consideration of the risk in selecting the S/R alternative.

Figure 5 provides a decomposition of the RRR alternative's operational cash flow. The cost of refurbishing the satellite is defined as a percentage of the RRR satellite cost. All other variables and the computation of RRR  $\Delta$  CF are similar to those described in the S/R alternative.

The R&R  $\Delta$  cash flow is shown in Figure 6. The descriptions of its variables are analagous to those already given. The benefit of the R&R alternative is in the fact that with satellites of longer design life, fewer will be needed in the program.

The direct values already discussed are all that are used in the cost-benefit analyses of the four studies reviewed in Chapter 2. They assume a 100% success rate and therefore, no value penalty due to risk. In addition, indirect values are not considered. Indirect values represent the intangible benefits an alternative may yield. DA provides a means of incorporating risk and indirect values into the value of an alternative.

The decision maker's overriding goal is to meet the satellite availability requirements of the program. There are several risk factors that influence the attainment of the goal. Launch failures, satellite failures, and program delays are risks in any alternative. The S/R and RRR alternatives have additional sources of risk.

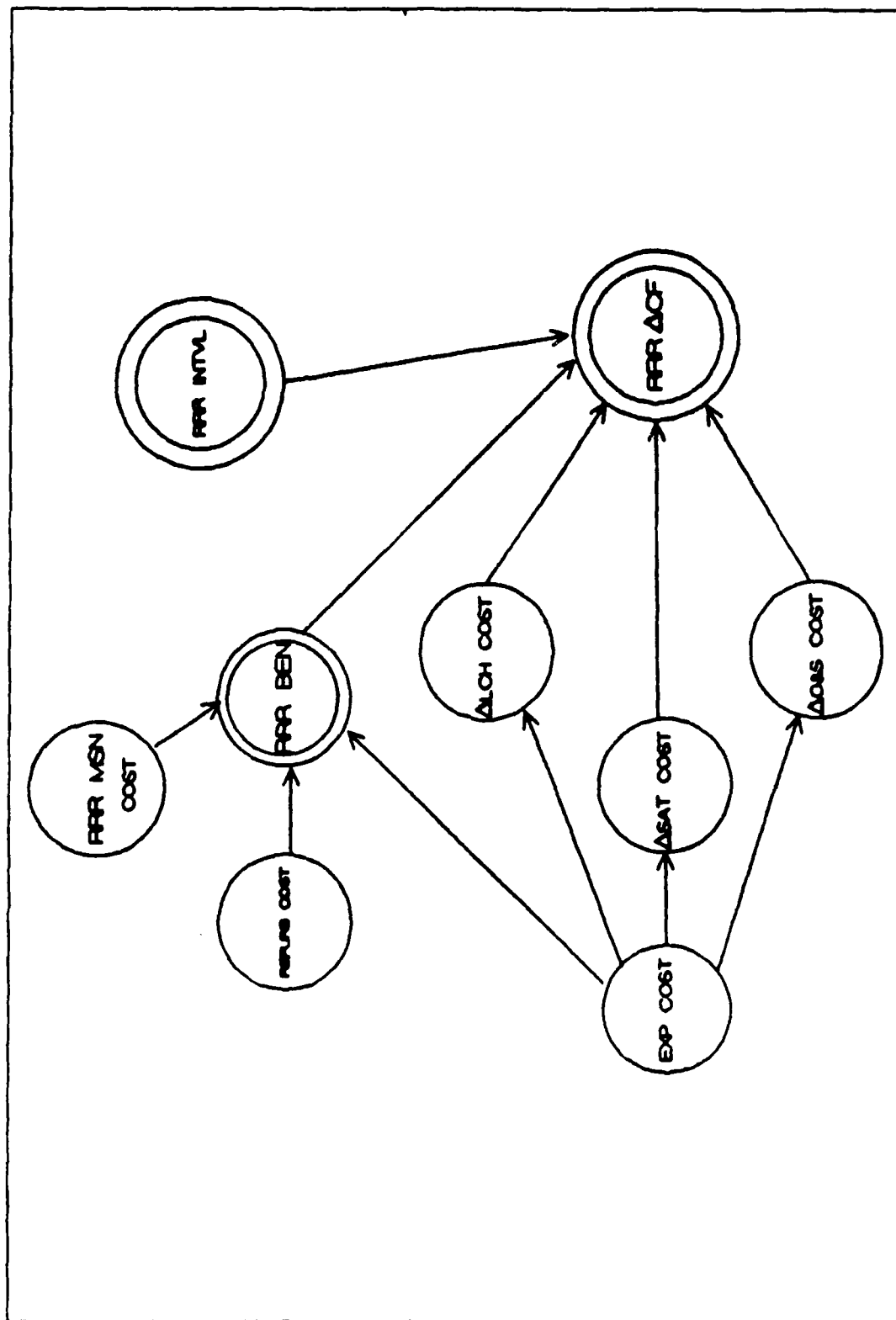


Figure 5. RRR  $\Delta CF$  Decomposition

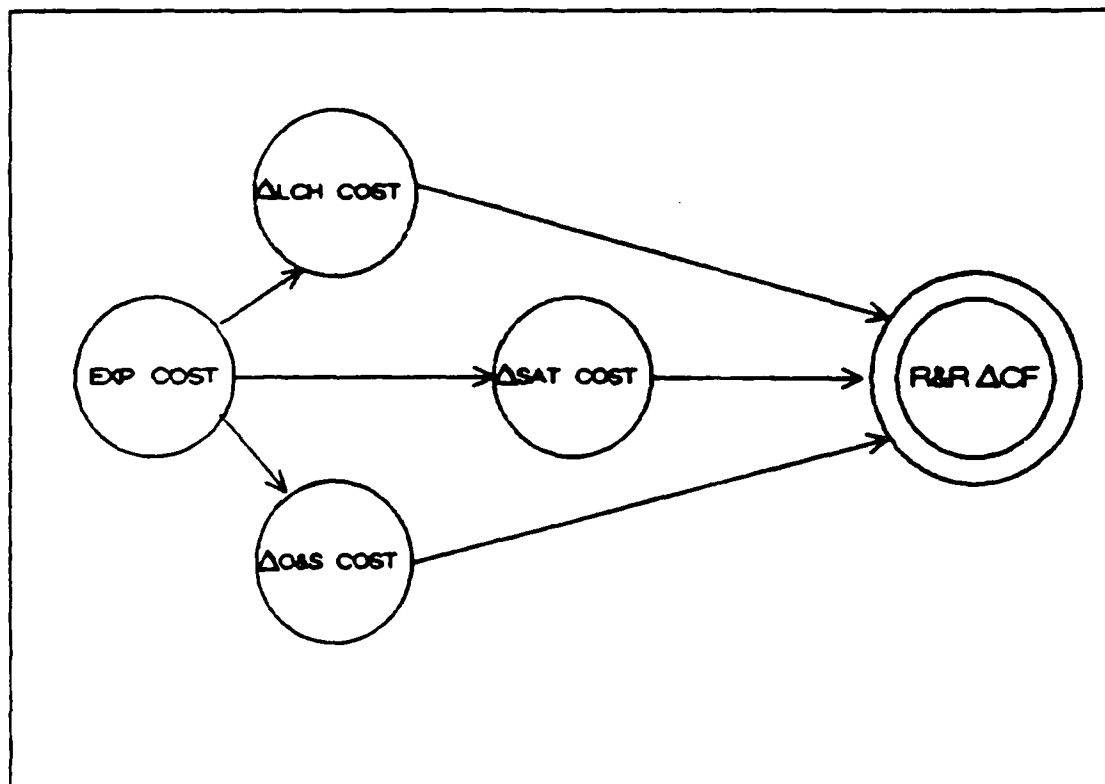


Figure 6. R&R  $\Delta$ CF Decomposition

Any satellite entering development in the near future and designed to use S/R or RRR capabilities is depending on a capability that may or may not exist when it begins its operational phase. Currently, only a rudimentary capability exists centered on the shuttle. Space stations and OMVs only exist as budget line items. The availability of the capability, if it exists, is also a concern. Shuttle flight schedules are tight and there is a considerable backlog of missions. The decision maker may be depending on routine resource availability when, in reality, it may be far from routinely available. Finally, any S/R or RRR mission may fail.

Risk cannot be eliminated, but the decision maker can bring the risk to an acceptable level. The schedule of missions built thus far for each alternative is a minimum schedule. The decision maker can add additional

launchers and satellites as backups to bring the minimum schedule up to an acceptable level of risk. This is done now for expendable satellites. Spare satellites are stored or placed in orbit as on-orbit spares. The same can be done for any alternative to account for the risks associated with that alternative.

The RISK CF variable collects three variables reflecting risk (see Figure 7). SAT FAIL and LCH FAIL are the decision maker's assessments of satellite or launch failure possibilities that would result in the premature loss of the satellite. MSN SCS, mission success, is his assessment of a S/R or RRR mission's chance of success. A schedule of additional launchers and satellites is then constructed interactively with the decision maker for each alternative. The schedule reflects the decision maker's determination of the magnitude and the timing of the risk. This risk schedule represents what is needed to bring each alternative to the same acceptable risk level.

The schedule also represents a cash flow to be used in the value variable's mathematical function (value function). This cash flow can be either a cost or a benefit for an alternative. Once again, an alternative's cash flow is compared to the default alternative's for the cost or benefit determination. For example, in an expendable-satellite two launchers and two satellites are required in the first year of the program to account for the risk. The S/R alternative has the same additions and also requires an additional launcher and satellite in the third year to backup the first scheduled S/R mission. This addition in the third year is the risk penalty of the S/R alternative vis-a-vis the expendable default

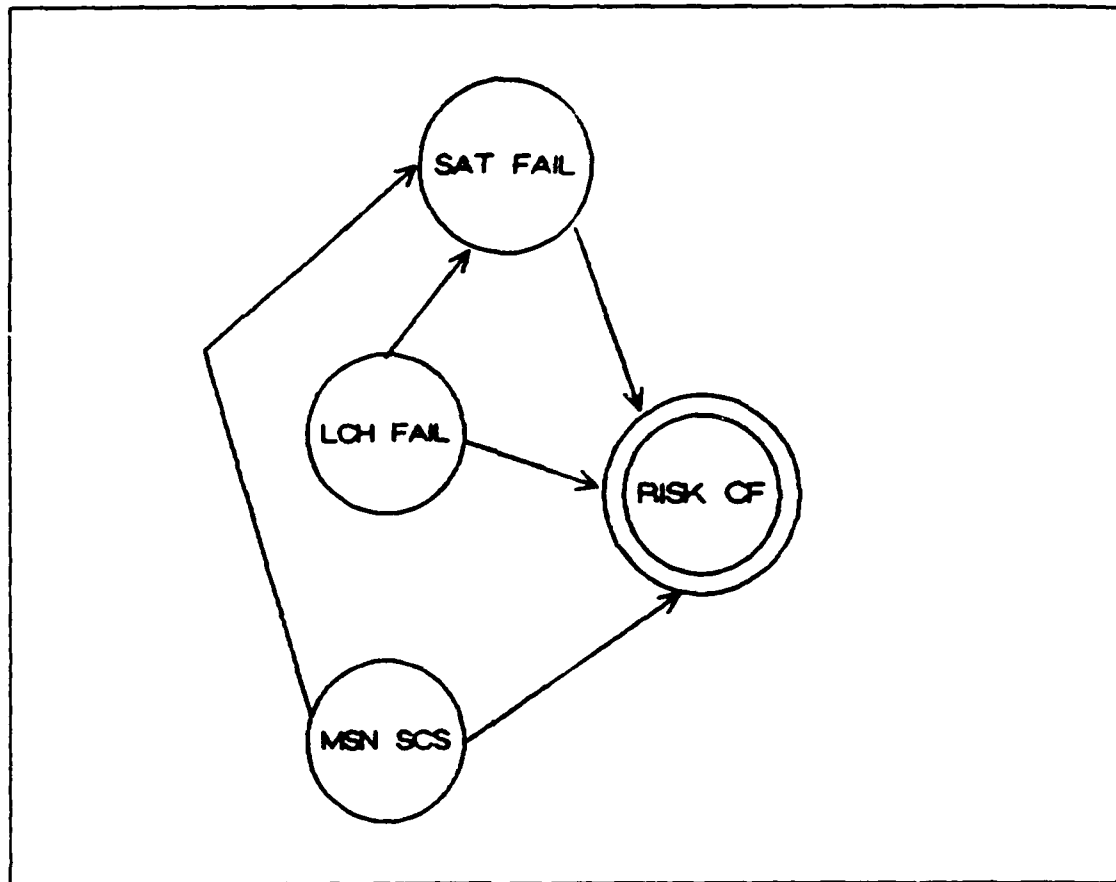


Figure 7. RISK CF Decomposition

alternative. This third-year cost is the cash flow used in the value function. The last element of an alternative's value is indirect value.

Indirect value represents the intangible benefits and costs of an alternative. Most analyses make no attempt to quantify them. Yet, they are often decisive in the selection of an alternative. INTAN is the variable that collects the decision maker's estimates of these intangibles. Its decomposition is illustrated in Figure 8.

Four sources of indirect value are included. The first three deal with the satellite. UPDATE reflects the value associated with being able to upgrade a satellite during its operational career. This value is a possible by-product of the S/R and RRR alternatives. SURV, survivability,



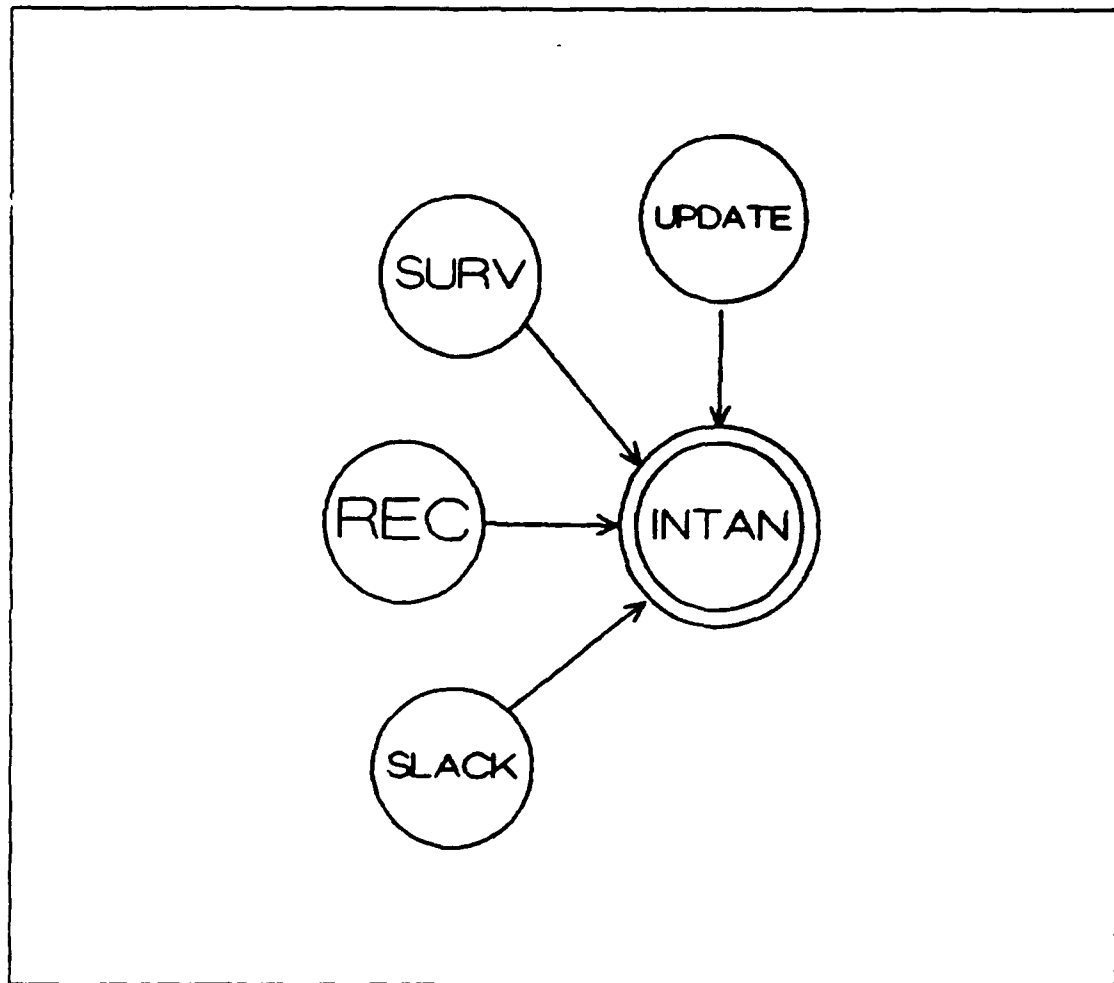


Figure 8. INTAN Decomposition

is also a possible by-product of the S/R alternative. It reflects the judgement that an S/R satellite is less constrained by fuel considerations and can maneuver more freely. S/R and RRR satellites are more easily recovered and this value is in the REC variable. Controlling space debris is an increasing problem. Space piracy becomes less far-fetched as more nations develop a shuttle capability. There is technology and intelligence value in another nation's satellites even after they become inoperative (legal issues aside). These are some of the considerations that can be included in the REC variable.

The last variable, SLACK, deals with an issue already discussed--satellites having residual life at the defined end of a program. The residual life provides a measure of time slack in fielding any follow-on program. One possibility for determining this value is to take the percentage of design life the residual life represents and take this percentage of the satellite cost and launch cost. This is then converted to a cash flow representing the benefit of those residual years. For example, a 10-year design-life satellite has 5 years of residual life. The launch and satellite cost is 200 million dollars. The benefit of the residual life is the net present value represented by a cash flow of 20 millions a year for those five years.

The intangible benefits and costs described are not all inclusive. It is impossible to cover the full range of possibilities. However, any important factor can be included at the decision maker's discretion. The value judgements required of the decision maker are subjective but the choice between alternatives is a combination of subjective and objective values.

#### Value Modeling

The final top-level influence diagram is depicted in Figure 9. The value of all aspects of the program are collected at the value variable. It is composed of the direct value of the R&D phase and the operational phase, the risk value, and the indirect value for each alternative. This collection can be thought of as a series of constant-year-dollar cash flows including benefits and costs for each series of outcomes that are possible for each alternative. The value function discounts the combined cash flows



into a single net present value (NPV) for each alternative's possible outcomes.

Recognize that each random variable and decision variable has an underlying tree. The branches of a tree are discrete approximations of the cumulative probability function for a random variable or are the choices for a decision variable. The influence diagram graphically depicts how these individual trees are combined into a composite tree for each alternative. A path through the tree describes a complete possible result for an alternative. The value function gives a value to that path.

Normally, the resulting path values are converted to utilities to reflect the decision maker's attitude toward risk. The choice between alternatives is based on a comparison of the expected utilities,  $E(U)$ s, of the alternatives. The default alternative (expendable satellites) has a  $E(U)$  of zero. The alternative, including the default alternative, with the highest  $E(U)$  is the preferred strategy. In the case of a risk neutral decision maker, the choice is made based upon expected value  $E(V)$ .

#### Spreadsheets

A total of six spreadsheets, two for each of the three alternatives, was developed for use with the model. The influence diagrams were directly converted into the spreadsheets. All variables with the exception of the intangible benefits (INTAN) are included. Each spreadsheet uses the applicable variables for the alternative it reflects to compute the direct and risk cash flows for the alternative. It combines these into a NPV for the combination of variables entered into the spreadsheet. The variables can be changed to compute the NPV for each possible overall outcome of the alternative. Rolling back the NPVs with the probability and

decision trees must be done manually or with another DA software package.

The spreadsheet documentation is included in Appendix B.

The pilot model covers a multitude of possible programs and scenarios. For that reason, many of the variables cannot be completely detailed. They depend on a particular program and scenario application. However, the general sensitivity of benefit and cost to several of the variables in any program is possible. This is done in Chapter 4. An example of the model's application is presented in the remainder of this thesis by applying the model to a hypothetical program.

#### IV. Direct-Value General Sensitivity Analysis

##### Overview

The direct value of an alternative compared to the expendable design strategy is contained in a very simple relationship. There is a larger upfront cost required to pursue an alternative design strategy. The alternative will have a positive direct value if this upfront cost is more than offset by a lower per-mission cost during the operational phase of the program. Figure 10 depicts a cash flow for a single satellite throughout a program.

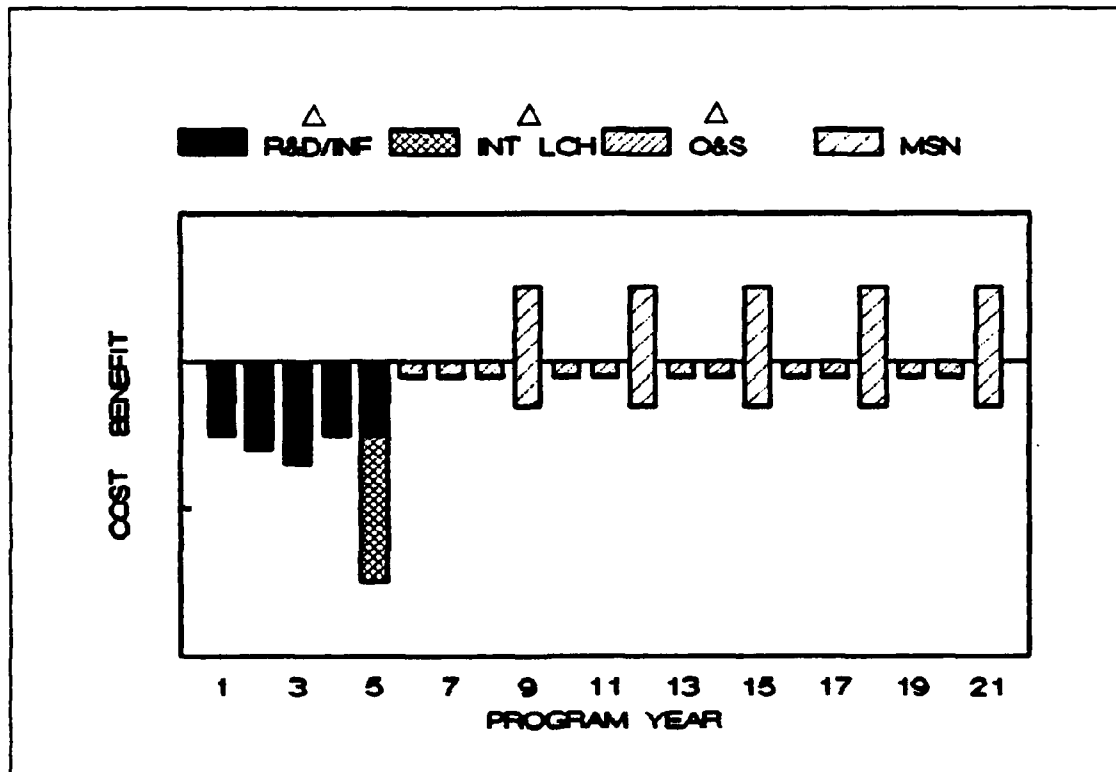


Figure 10. General Cash Flow For a Single Satellite

The cash flow in Figure 10 represents the additional costs incurred and avoided for an alternative compared to an expendable satellite throughout a representative program. The additional upfront cost is the sum of the additional R&D/infrastructure costs ( $\Delta R\&D/INF$ ) and additional launch/satellite costs for the initial launch ( $\Delta INT LCH$ ). The costs during the operational phase are the additional recurring costs such as O&S, refurbishment of a retrieved satellite, orbit-replaceable-unit (ORU) purchases, and the cost of the service/repair or retrieval mission. A per satellite basis is used for the analysis, but this description can be extended to a program with any number of satellites. Each service/repair or retrieval mission avoids the need to launch an expendable satellite. This is the benefit of the alternatives represented in the figure. The figure depicts a benefit as a bar above the zero line and an additional cost as a bar below the zero line.

The cash flow is then simplified. All upfront costs are discounted into a single value. All operational costs are discounted into a single benefit value for each mission. The assumption is made that each mission has a net benefit (the cost avoided is greater than the cost incurred on each mission). This result of this process is represented in Figure 11. A single flow of net benefits is balanced against the upfront cost. This is the process used in the general sensitivity analysis.

The variables effecting the relative magnitude of the benefits and the upfront cost will be explored. The DA model of the previous chapter detailed these variables. A baseline program of 25 years, with a five-year R&D phase and a 20-year operational phase, is used as a starting point. From that point, variables are changed to determine their effects on the

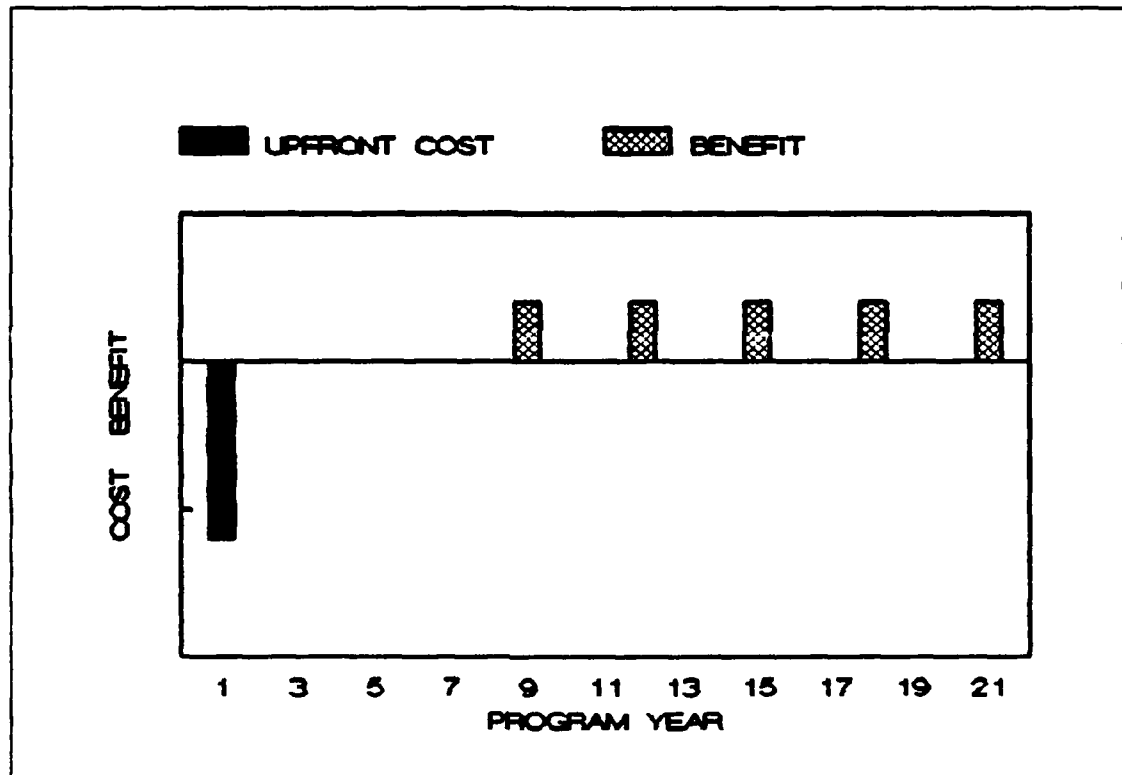


Figure 11. Simplified Cash Flow

upfront cost/benefit relationship. The purpose is to discover what aspects of the variables, in a qualitative sense, tend to favor the service/repair or retrieval alternative.

#### Discount Rate, Program Length, and Mission Interval

A discount rate converts an alternative's cash flow into a present value for comparison between alternatives. The discount rate represents the minimum attractive rate of return for a program (5:149). The discount rate has a significant impact on any long program where an investment is made upfront and the benefits are in the future. The upfront costs are discounted for a short span of time and the future benefits are discounted for a greater number of years. A low discount rate would encourage investments for distant future benefits. This is because the net present



value of the benefits would not be heavily discounted. On the other hand, a high discount rate might discourage any such investment. The future benefits are so heavily discounted that their net present value minus the net present value of the upfront costs results in a net loss. A decision maker must consider many factors in selecting a discount rate.

Analyses for government agencies tend to use an average-cost-of-borrowed-money evaluation to set the discount rate. There may be reasons to use a higher discount rate. A higher rate would serve as a discriminator. This is used in the case where there are more opportunities than limited investment capital will allow. A higher rate could also reflect the risk attitude of the decision maker if risk was not already considered in the analysis. A higher rate would also reflect the adverse effects of government borrowing--inflation and the deficit (5:490-493).

The sensitivity analysis in this chapter uses a range of from 5 to 12% for the discount rate. The current interest rates paid by the government on bonds are about 7-10% (Series EE and 30-year bonds). In addition to the discount rate, the timing of the benefits is very important.

The timing of the benefits is a function of the interval between service/repair or retrieval missions. The mission interval is also correlated with the satellite design life. Naturally, a shorter design life requires a shorter mission interval. A shorter interval in a program yields more opportunities for benefit. This allows the capital recovery (CR) of the upfront cost to be spread across more missions. The result is a lower required benefit per mission to equal the net present value of the upfront costs. In a 20-year operational phase, six missions are required for a three-year mission interval or one mission for a ten-year mission

interval. The result is that in the shorter three-year interval, each mission must have a net benefit equal to 65% of the upfront cost (with  $i^*=10\%$ ) to realize the 10% minimum rate of return. This translates to a benefit equal to 65% of the upfront cost per mission to equal the net present value of the upfront costs. In the ten-year interval, this increases to 418% for the single mission. Figure 12 depicts the capital recovery required per mission as a percentage of the upfront cost for a range of discount rates.

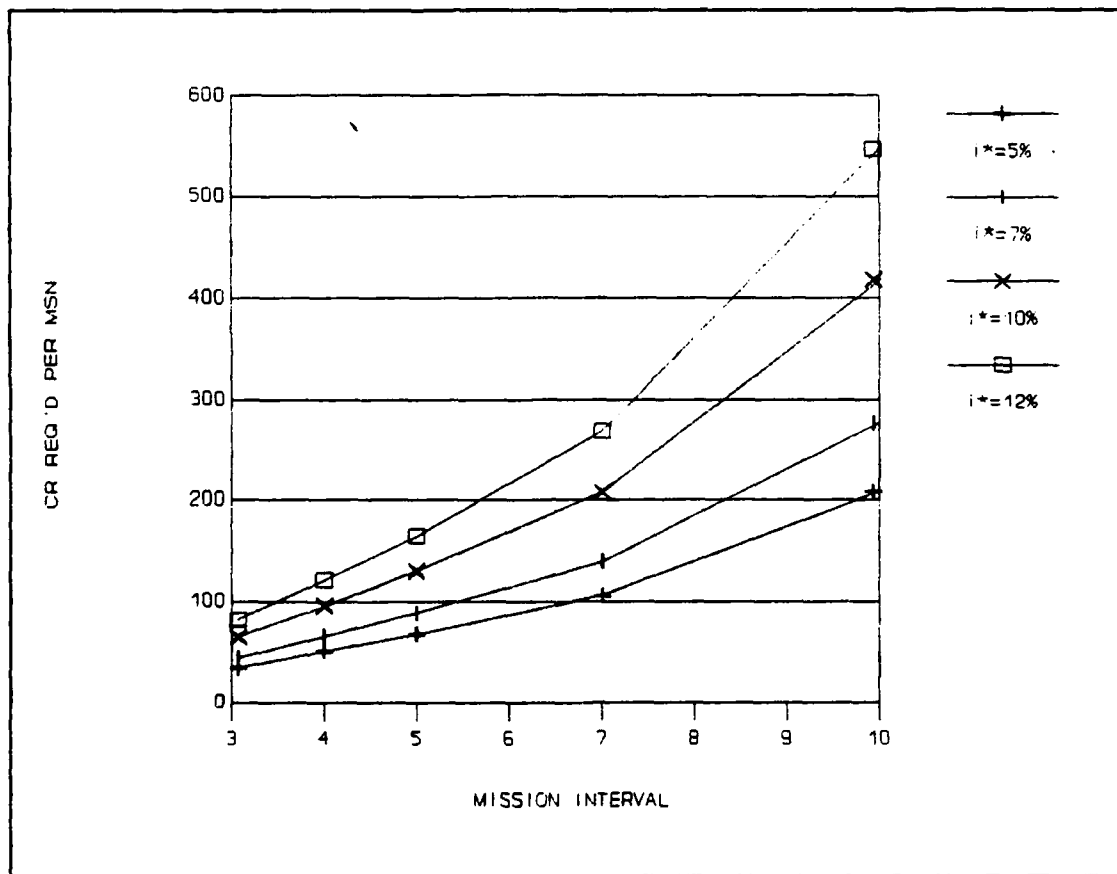


Figure 12. Capital Recovery Required Per Mission as a % of Upfront Cost, 20-YR Operational Phase

The total capital recovery (CR) required of the program, net required benefit of the program, as a function of mission interval and discount rate is illustrated in Figure 13. The total CR is derived from multiplying the CR per mission times the number of missions in the twenty-year operational phase. The three-year interval requires a total CR of 390% for a 10% discount rate (six missions in a twenty year operational phase at 65% per mission). The entire program of six S/R or retrieval missions must return a net benefit of 390% to equal the net present value of the upfront costs. The ten-year interval requires the same 418% for its total CR as its per mission CR because there is only one mission. The interaction of the number of missions and capital recovery required per mission results in the four and five-year intervals having a lower total CR requirement.

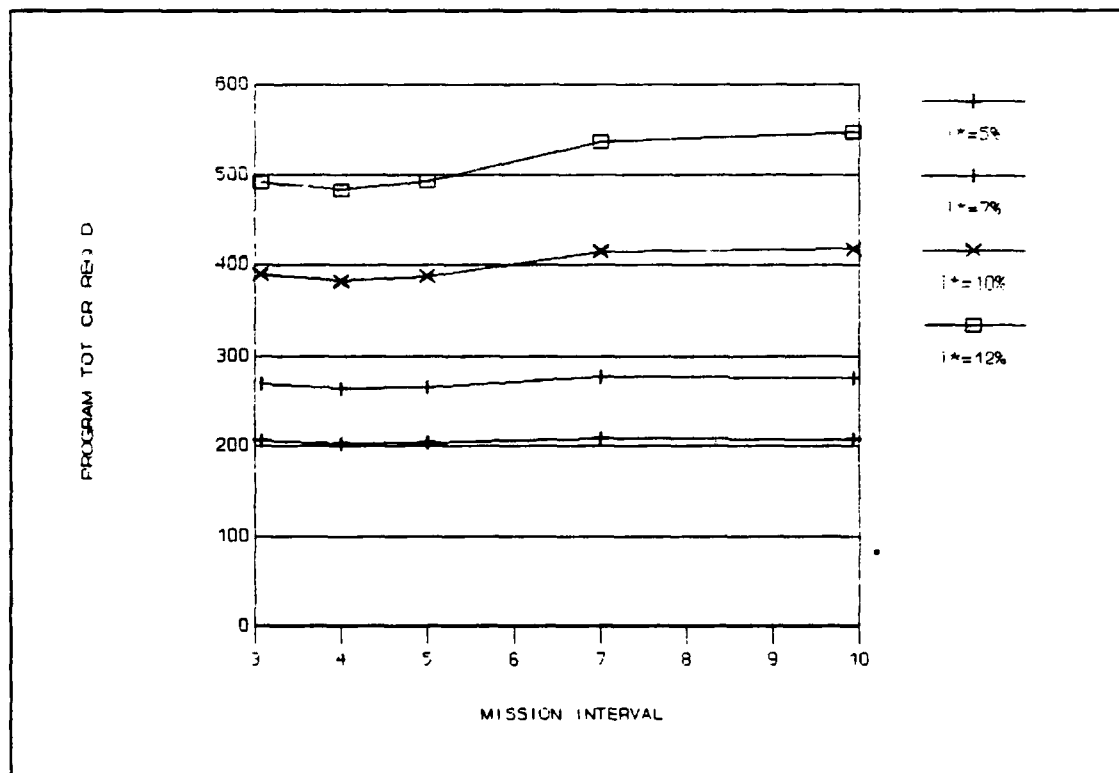


Figure 13. Total Capital Recovery Required as a % of Upfront Cost, 20-YR Operational Phase

Without actual dollar values, only a qualitative sensitivity analysis is possible. Increases in the upfront cost translate into a higher dollar burden for the benefits (higher capital recovery per mission) in the operational phase to offset. The percentages in the figures become percentages of a higher dollar value. If the upfront cost is small, the difference between 65% and 418% may not be important. But what if the upfront cost is not small?

Remember, the benefit of a service/repair or retrieval mission is that a new satellite does not need to be launched. The benefit comes at the cost of the service/repair or retrieval mission. The net benefit of a mission is affected by the factors that determine the difference between costs incurred and costs avoided. For example, a significant reduction in launch costs would decrease the net benefit of a S/R or retrieval mission, as would inexpensive expendable satellites. An increase in the cost of a S/R or retrieval mission would have the same effect. Several observations are possible.

It will be much less difficult to meet the cost recovery requirements of a short-interval program. The required difference between cost incurred and cost avoided, required benefit, is much less than in the long-mission-interval program. To obtain a 418% benefit (ten-year interval,  $i^*=10\%$ ) would require a relatively more expensive expendable satellite and launch cost than a 65% benefit (three-year interval,  $i^*=10\%$ ). As the frequency of missions decreases, larger costs must be avoided to obtain the required benefit.

Consider a satellite with a 10-year design life/mission interval that had a 100 million dollar upfront cost. The required benefit is 418 million

dollars for the single service/repair or retrieval mission that would occur in a 20-year operational phase. If the expendable satellite and launch cost totaled 400 million dollars, it would be impossible to get a 418 million dollar benefit. One can't avoid 418 million dollars on a 400 million dollar cost. With a 3-year design life/mission interval for the same example, it is possible to return a 65 million dollar benefit per mission. In the case of a short design life/mission interval, the lower required benefit per mission is possible for a much wider range of expendable satellite and launch costs. This conclusion can be extended to all the variables that determine the net benefit of a mission. The possibility of achieving the required benefit is less sensitive, for a shorter mission interval, to the factors that determine the benefit.

This fact is true regardless of program length. Changing the program length only effects the magnitude of the required benefits. The same conclusion applies in any comparison of mission intervals given a program length. Figures 14 and 15 represent comparable cost recovery percentages for a thirty-year operational phase. The important fact to note is that the percentages for the capital recovery per mission have decreased. The required net benefit is spread across more missions in a longer program. The total capital recovery increases because the greater number of missions has a greater effect on total capital recovery than the lower capital recovery per mission. The conclusion can be made that in comparing programs of different lengths, it will be easier to meet the required benefits of a longer program. Service/repair or retrieval will tend to be favored in long programs involving expensive expendable satellites with short design lives and high launch costs.

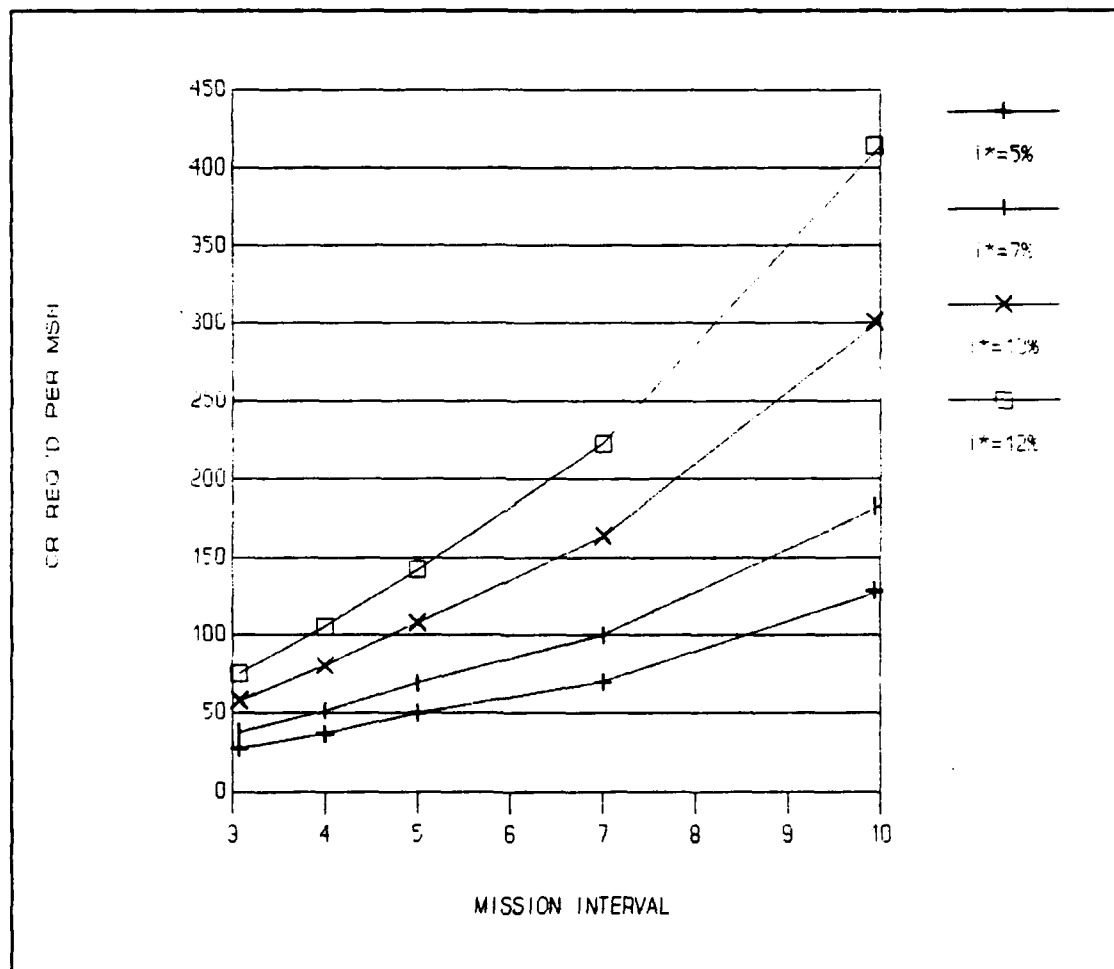


Figure 14. Capital Recovery Required Per Mission as a % of Upfront Cost, 30-YR Operational Phase

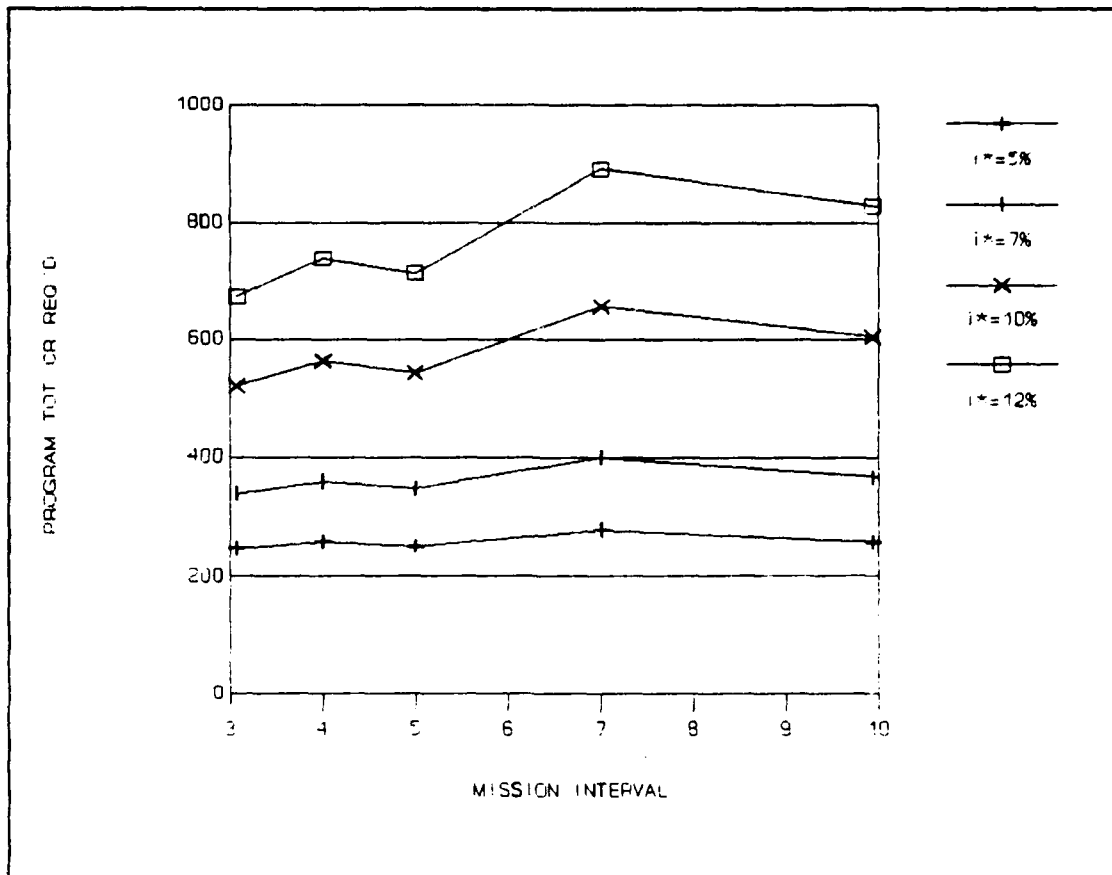


Figure 15. Total Capital Recovery Required as % of Upfront Cost, 30-YR Operational Phase

#### R&D Stretchout

An R&D stretchout will delay the start of the operational phase and effect the capital recovery required. The possible benefits are pushed further into the future and then are further discounted. The result is an increase in the capital required per mission and in the total capital recovery required of the operational phase. The additional capital recovery required per mission is depicted in Figure 16 for a 10% discount rate and for five different mission intervals. Figure 16 is based on a planned five-year R&D phase within a 25-year program. The shorter the

interval, the less the effect of a delay. For example, a three-year interval program, delayed one year, suffers the penalty of an additional 6.5% capital recovery per mission required. A ten-year interval program has an additional 42% capital recovery per mission required. For a longer mission interval, the penalty can drive the per-mission-capital-recovery-requirement out of the realm of the possible.

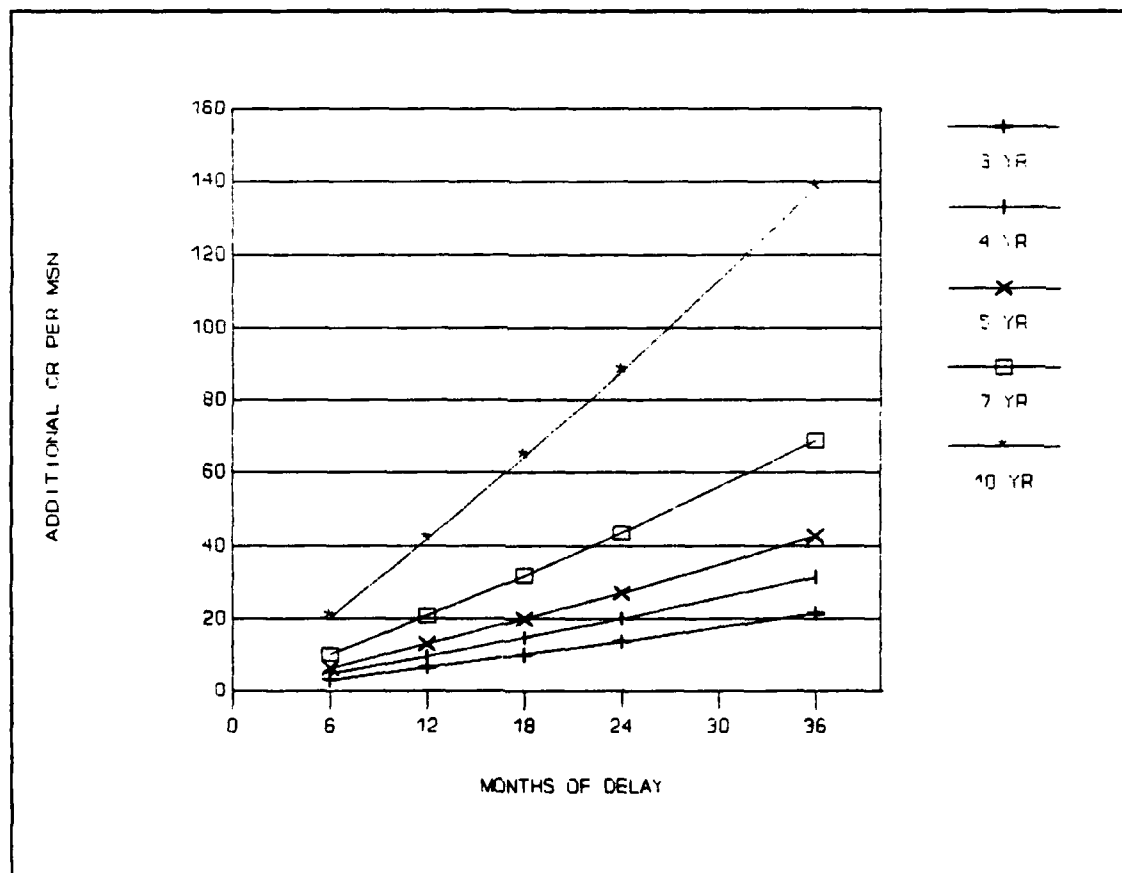


Figure 16. Additional Capital Recovery Required per Mission Due to R&D Stretchout as a % of Upfront Cost,  $i^*=10\%$ , 20-YR Operational Phase

The total additional capital recovery required as a result of a delay in the R&D phase is illustrated in Figure 17 for a discount rate of 10%.



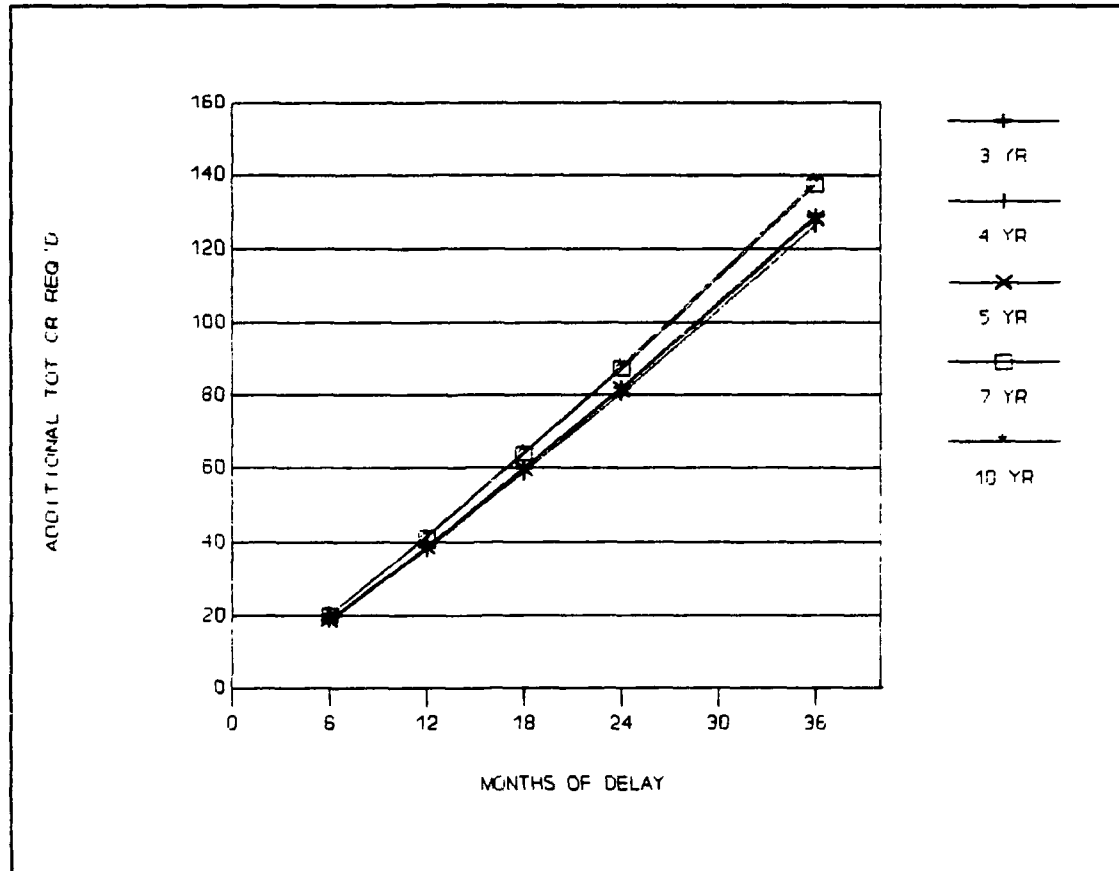


Figure 17. Additional Total Capital Recovery Required as a % of Upfront Cost Due to a R&D Stretchout,  $i^*=10\%$ , 20-YR Operational Phase

Changing the planned length of the R&D phase has the same capital-recovery effects. Longer R&D phases impose larger capital recovery requirements on the S/R or retrieval missions. Appendix C has several more graphs, similar to Figures 16 and 17, for other discount rates.

#### Number of Satellites

A program involving several satellites will favor the S/R or retrieval alternatives. The size of the required capital recovery per mission will not change, but the upfront costs are spread among the total number of

satellites. The capital recovery percentages are then percentages of a smaller number (after the upfront costs are parceled on a per-satellite basis).

#### Summary

Using a generalized cost-benefit cash flow demonstrates several aspects of a satellite program that tend to favor the service/repair or retrieval alternative. A program of long duration, involving expensive satellites and launch costs and satellites of short design life tend to favor the service/repair or retrieval options. Risks involving a good possibility of an R&D stretchout may make the required capital recovery unachievable for longer-design-life satellites in particular.

These are all relative comparisons and are only intended to signal trends that favor the service/repair or retrieval alternatives. They do not rule out satellite programs that seemingly are not favored. In those cases, a unique combination of variables may make service/repair or retrieval feasible. With a specific program, the trade-offs become concrete. The remainder of the thesis explores a hypothetical program using the DA model developed.

## V. Scenario and Deterministic Sensitivity Analysis

### Overview

A scenario involving a new hypothetical satellite program was developed. The program is based on a RAND study concerning past Defense communications satellites (18:100). A baseline program using five-year-design-life communications satellites is the default alternative. Two other alternatives are considered--increasing the reliability (R&R) to lengthen the design life or to design the satellite for on-orbit service/repair (S/R). The retrieval option was eliminated due to the size of the satellites. They will be too large to retrieve and return for refurbishment. Another alternative is being considered for a follow-on study. This alternative considers the possibility of combining increased design life and service/repair features (R&R and S/R) into the satellite.

Major Sheridan served as the decision maker (program manager) in this scenario. The DA model was then applied to the hypothetical program.

### Scenario

The scenario begins in 1988 with the decision maker ready to begin a new satellite program. The new program, DC-X, requires an operational constellation of four communications satellites. The R&D phase will begin in 1989 and is planned to end in 1996. The DC-X satellites are to replace the current DC-W satellites as they reach the end of their design life. The first two DC-W satellites are scheduled for replacement in 1997 and the second pair in 1999. Expendable launch vehicles will be used for all launches. The satellites will be launched in pairs, two per expendable launch vehicle. A follow-on program for DC-X will be phased-in in 2022.

There are three alternative configurations for the DC-X satellite. The decision must be made as to which configuration enters the R&D phase. The three alternatives will seek common improvements for the communications capabilities of the DC-X satellite vis-a-vis DC-W. The choice of configuration centers on how the constellation will be maintained. The default alternative will continue to use a five-year design life and expendable satellites. The R&R alternative will seek to extend the design life to ten years by increasing component reliability or redundancy. The S/R alternative will retain the five-year design life but incorporate service/repair features into the satellite. Several operational details concerning the S/R alternative are known.

The orbits of the DC-X satellites will require the shuttle and the orbital maneuvering vehicle (OMV) to accomplish the service/repair missions. The first service/repair missions would be scheduled in 2002. At this time, NASA anticipates the OMV to be operational in the late 1990's. Several preliminary cost details are also known.

The program manager has been directed to use a 10% discount rate for all present value computations. The baseline expendable satellite will cost 225 million dollars and launch costs are 108 million per satellite (based on Titan IV data, (16:34)). The R&D cost is also established. All of these are considered firm costs because the expendable satellite does not represent any R&D uncertainty. In this configuration, the DC-X will simply be a slightly improved DC-W satellite and the DC-W cost data is established. The shuttle and OMV will be used on a per-mission-charge basis from NASA and the quoted price is 142 million dollars per mission

(subject to change). The pilot DA model was then applied to this hypothetical program.

#### Model Application

The scenario has defined all the system variables for the program definition (PROG DEF, see Figure 2). This represents much the same information that would be available beginning any new program. The minimum schedule of launch events was built from this information for all three alternatives. The R&D budget for the expendable alternative is also known. This timeline information is presented in Table 1.

Table 1. Known Timeline Information

| <u>YEAR</u> | <u>EXP R&amp;D</u><br><u>(millions)</u> | <u>YEAR</u> | <u>#EXP SAT</u><br><u>LAUNCHED</u> | <u>#R&amp;R SAT</u><br><u>LAUNCHED</u> | <u>#S/R SAT</u><br><u>LAUNCHED</u> | <u>S/R</u><br><u>MISSIONS</u> |
|-------------|---|-------------|------------------------------------|--|------------------------------------|-------------------------------|
| 1989        | 40                                      | 1997        | 2                                  | 2                                      | 2                                  |                               |
| 90          | 53                                      | 1999        | 2                                  | 2                                      | 2                                  |                               |
| 91          | 65                                      | 2002        | 2                                  |  |                                    | 2                             |
| 92          | 62                                      | 2004        | 2                                  |  |                                    | 2                             |
| 93          | 22                                      | 2007        | 2                                  | 2                                      |                                    | 2                             |
| 94          | 20                                      | 2009        | 2                                  | 2                                      |                                    | 2                             |
| 95          | 16                                      | 2012        | 2                                  |  |                                    | 2                             |
| 96          | 10                                      | 2014        | 2                                  |  |                                    | 2                             |
|             |   | 2017        | 2                                  | 2                                      |                                    | 2                             |
|             |   | 2019        | 2                                  | 2                                      |                                    | 2                             |

Because the expendable satellite is a block improvement of an existing satellite, its cost data is relatively certain. The expendable satellite cost data is treated deterministically for this reason. The ranges of the chance variables for the remainder of the model were then gathered.

The decision maker provided the estimates for the ranges of the chance variables. In an actual program, estimates for the uncertainties may come from the decision maker or his experts in those areas. Low, nominal, and

high values were obtained for the chance variables. These represent the 10, 50, and 90 percentile for the chance variables. The results of the decision maker's estimates are presented in Table 2 according to alternative (S/R or R&R).

Table 2. Chance Variable Range Estimates

| <u>S/R</u> |                |             | <u>VARIABLE</u> | <u>R&amp;R</u> |                |             |
|------------|----------------|-------------|-----------------|----------------|----------------|-------------|
| <u>low</u> | <u>nominal</u> | <u>high</u> |                 | <u>low</u>     | <u>nominal</u> | <u>high</u> |
| 2%         | 5%             | 8%          | R&D Δ CF        | 5%             | 8%             | 10%         |
| 0          | 0              | 1           | R&D DLY         | 0              | 0              | 1           |
|            |                |             | (YEARS)         |                |                |             |
| 1          | 2              | 3           | INFRA CF        | 0              | 0              | 0           |
|            |                |             | (MILLION/YR)    |                |                |             |
| NO         | YES            | YES         | R&D SCS         | NO             | YES            | YES         |
|            |                |             | S/R MSN         |                |                |             |
| 5%         | 15%            | 25%         | COST            |                | N/A            |             |
| 5%         | 10%            | 15%         | ORU COST        |                | N/A            |             |
| 5%         | 10%            | 15%         | Δ SAT COST      | 15%            | 25%            | 30%         |
| 1%         | 1%             | 101%        | Δ LCH COST      | 0.3%           | 0.3%           | 100.3%      |
| .5         | 2.5            | 5           | Δ O&S COST      |                | NONE           |             |
|            |                |             | (MILLION/YR)    |                |                |             |
|            | ***            |             | INTAN           |                | N/A            |             |

Several points were made by the decision maker in the course of the interview to determine the ranges in Table 2. The large variation in the launch cost is due to an interesting possibility. The plan is to launch two satellites on a single booster. The decision maker felt there was a possibility that the weight and volume penalties involved in a serviceable/repairable or retrievable satellite might require a single satellite per booster for all launches.

He also felt that the additional infrastructure costs involved in the S/R alternative would largely center on personnel costs. The decision maker stated that no additional facilities would need to be constructed as

there are enough clean room facilities to meet storage requirements. The O&S costs would go toward paying those storage costs. No additional infrastructure or O&S costs were included for the R&R alternative. It, too, is an alternative based on expendable satellites and so there are no additional costs when compared with the default alternative.

The intangible (INTAN) range proved hard to determine. The question was approached from two perspectives. The first was from the perspective of the senior Air Force leadership. How much would they be willing to increase the program budget, in addition to the anticipated cost, to secure the intangible benefits? The second perspective was that of Congress and considered the same question. By considering the answers to these questions, it was hoped a dollar value could be placed on the intangible benefits. A range of value was obtained, but it was felt that these values should not be included initially. Alternatively, the intangible value will be introduced in a probability-value (P-V) diagram at the end of the analysis. The additional spares required for each alternative, RISK CF, was the last consideration for the decision maker.

The RISK CF variable was described in the model development. It includes the decision maker's assessment of possible launch and satellite failures as well as the S/R missions' successes or failures. It also captures the decision maker's assessment of where the risks occur in time.

To capture these assessments, the decision maker was presented with the launch schedules and S/R mission schedules of Table 2. These schedules represent the minimum required events for each mission--no failures. The decision maker then completed another schedule for each alternative to reflect the risk of failures. These risk schedules included additional

expendable launch vehicles (ELVs) and satellites for each alternative to serve as on-orbit or ground spares. The decision maker elected to have a dedicated ELV for each spare. Each alternative was brought to the same level of risk with respect to the operational requirement of maintaining four operational satellites. The risk schedules for each alternative are listed in Table 3. The decision maker confirmed that the total schedule for each alternative, combining the Table 2 and Table 3 schedules, were of equal risk in view of the operational requirement. He was indifferent to the choices based on ability to meet the operational requirement.

Table 3. Risk Schedules

| <u>Year</u> | <u>Expendable Sat</u><br><u>(ELV/Sat)</u> | <u>S/R Sat</u><br><u>(ELV/Sat)</u> | <u>R&amp;R Sat</u><br><u>(ELV/Sat)</u> |
|-------------|---|------------------------------------|--|
| 1997        | 1/1                                       | 1/1                                | 1/1                                    |
| 2002        | 1/1                                       | 1/1                                |  |
| 2005        |   | 1/1                                | 1/1                                    |
| 2008        | 1/1                                       |                                    |  |
| 2012        | 1/1                                       |                                    |  |
| 2015        |   |                                    | 1/1                                    |
| 2017        | 1/1                                       |                                    |  |

The decision maker felt that the greatest need for a spare was generated by the initial launch and bringing the satellite into operation once established in orbit. The risk schedules show a correlation between spares required and initial satellite launches for each alternative. Both the expendable and R&R alternatives require spares throughout the program to cover all initial satellite launches. The S/R alternative is front-loaded to cover the initial launches of the four satellites and to backup the first few service/repair missions. The decision maker felt that the early



service/repair missions may encounter difficulties but then the capability will mature.

The complete program schedule for each alternative has been completed. The schedules were then converted to cash flows for comparison. This was accomplished using the spreadsheets developed for the model. The default alternative, expendable satellites, served as the baseline cash flow. The default alternative served as the reference and was given a NPV of zero. Each alternative's, S/R and R&R, cash flow was converted to one reflecting the net differences between it and the default alternative. Figures 18 and 19 are the delta cash flows for each alternative and show the net differences using the nominal values for the variables. The delta cash flow for each alternative was then converted to a nominal NPV. The nominal delta cash flows served as the reference in conducting the deterministic sensitivity analysis (DSA) for each alternative.

#### Deterministic Sensitivity Analysis

The purpose of the deterministic sensitivity analysis (DSA) is to discover how sensitive the value of an alternative is to the uncertainty in each of its variables. The DSA is accomplished by starting at the nominal setting for each variable and establishing the nominal NPV for an alternative. One at a time, each variable is varied from its minimum to maximum setting. The resulting difference in NPV measures the sensitivity of the alternative's NPV to the uncertainty of the variable (5:129).

No probabilities are included for any of the variables. Because of this, the alternative may be insensitive to the uncertainty in any variable that has very little effect on the nominal NPV of an alternative. Further analysis is required to definitely establish insensitivity.

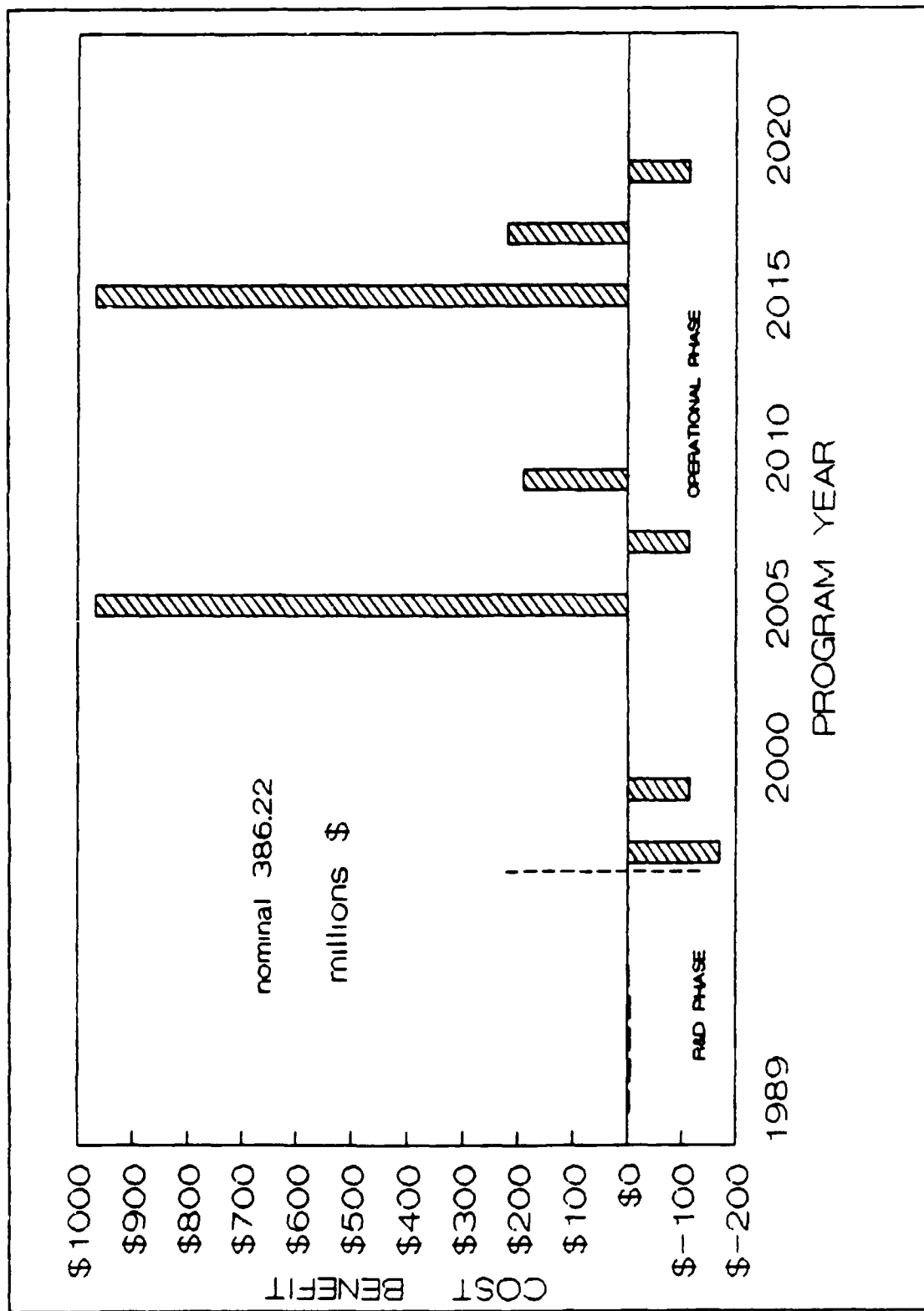


Figure 18. R&R Alternative--Cash Flow

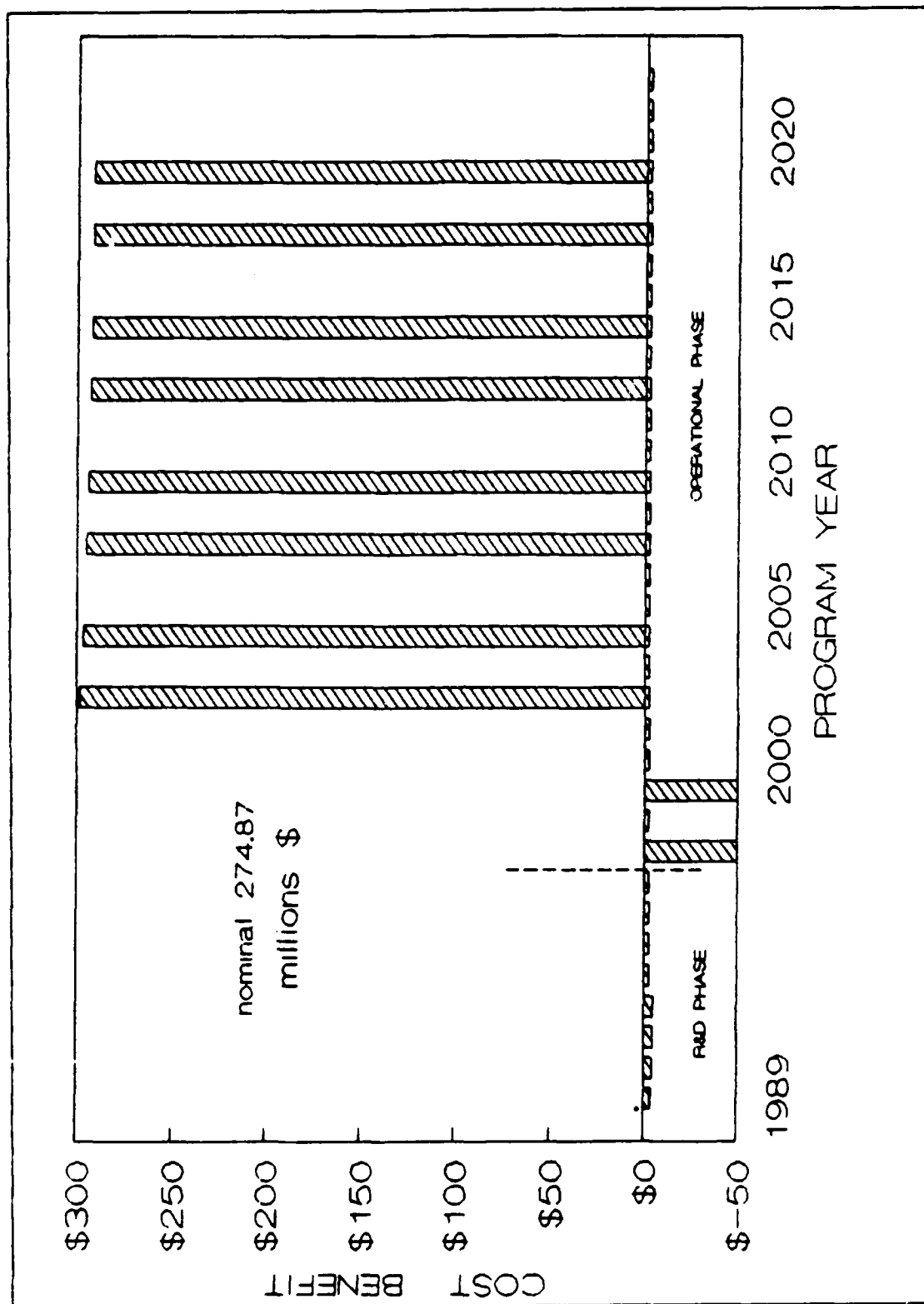


Figure 19. S/R Alternative--Cash Flow

A variable's range may influence other variables' effects on an alternative's NPV through preferential dependence. The preferential dependence is determined by the decision maker. Consider two variables, A and B, where B is preferentially dependent on A. Setting A to its high or low setting would alter the decision maker's preference and value for B. In preferential dependence cases, the variables must have their settings changed in concert. This will be the true measure of A's effect on the alternative's value.

An alternative is insensitive to the uncertainty in a variable if it, acting alone or with preferential dependence considered, has little effect on the nominal value of an alternative. A variable so identified can be set to its nominal setting for the remainder of the analysis. Regardless of the probability associated with the variable's outcomes, it will have relatively little effect on the value of the alternative.

Figures 20, 21, and 22 are the single variable effects on the nominal value for each alternative. Changing a variable's setting results in a change to the nominal delta cash flow and the net present value of the alternative. Tables 5 and 6, in Appendix E, are the numerical results of the DSA for this scenario.

The additional R&D funds,  $R\&D\Delta CF$ , to increase the satellite's reliability only caused a delta value of 10.5 million dollars in the R&R alternative. It has no preferential link to any other variable. For example, the decision maker would prefer low satellite costs regardless of whether the  $R\&D\Delta CF$  were high or low.  $R\&D\Delta CF$  was set at its nominal value cash flow for the remainder of the analysis.

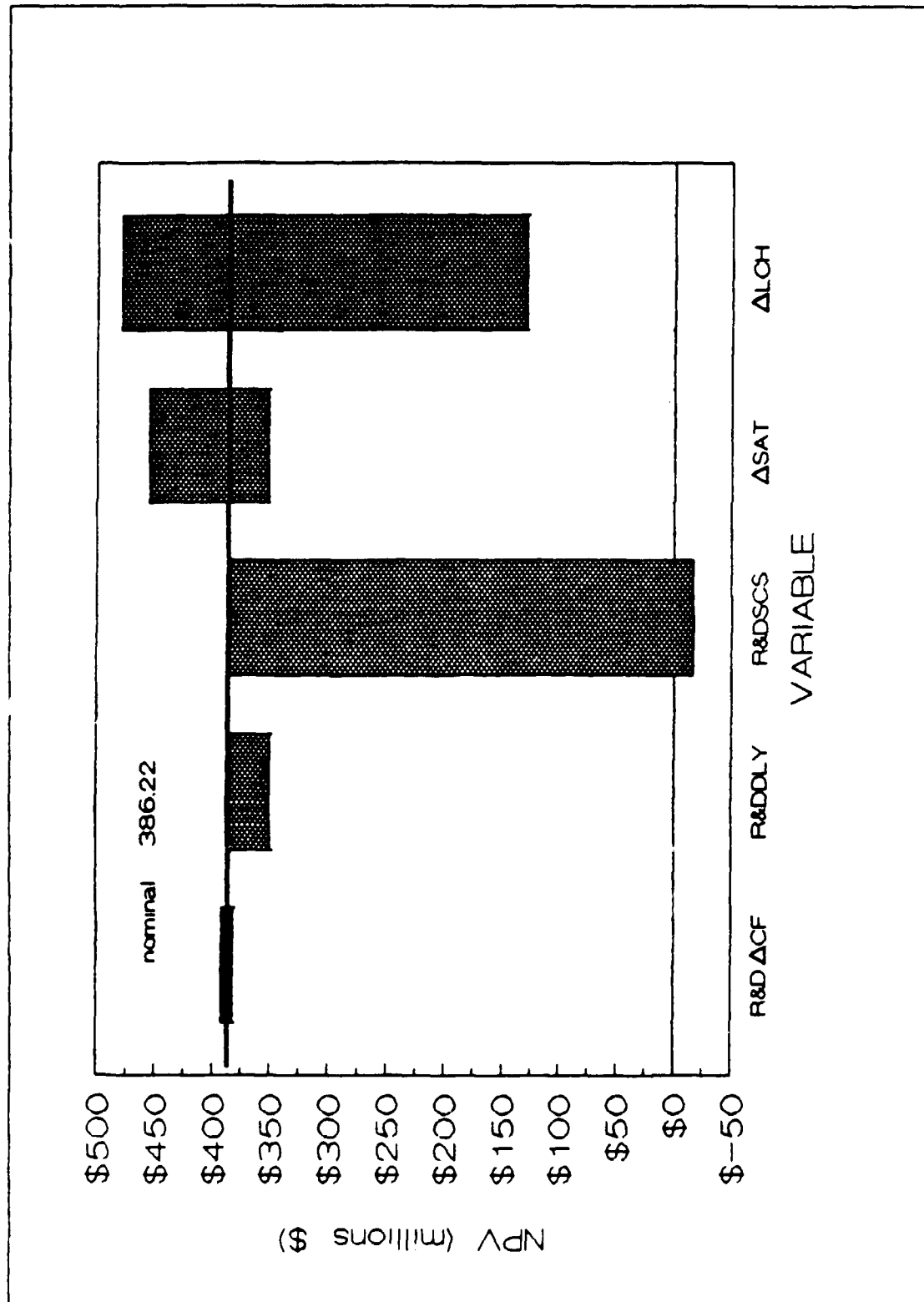


Figure 20. R&R Alternative--Deterministic Sensitivity Analysis

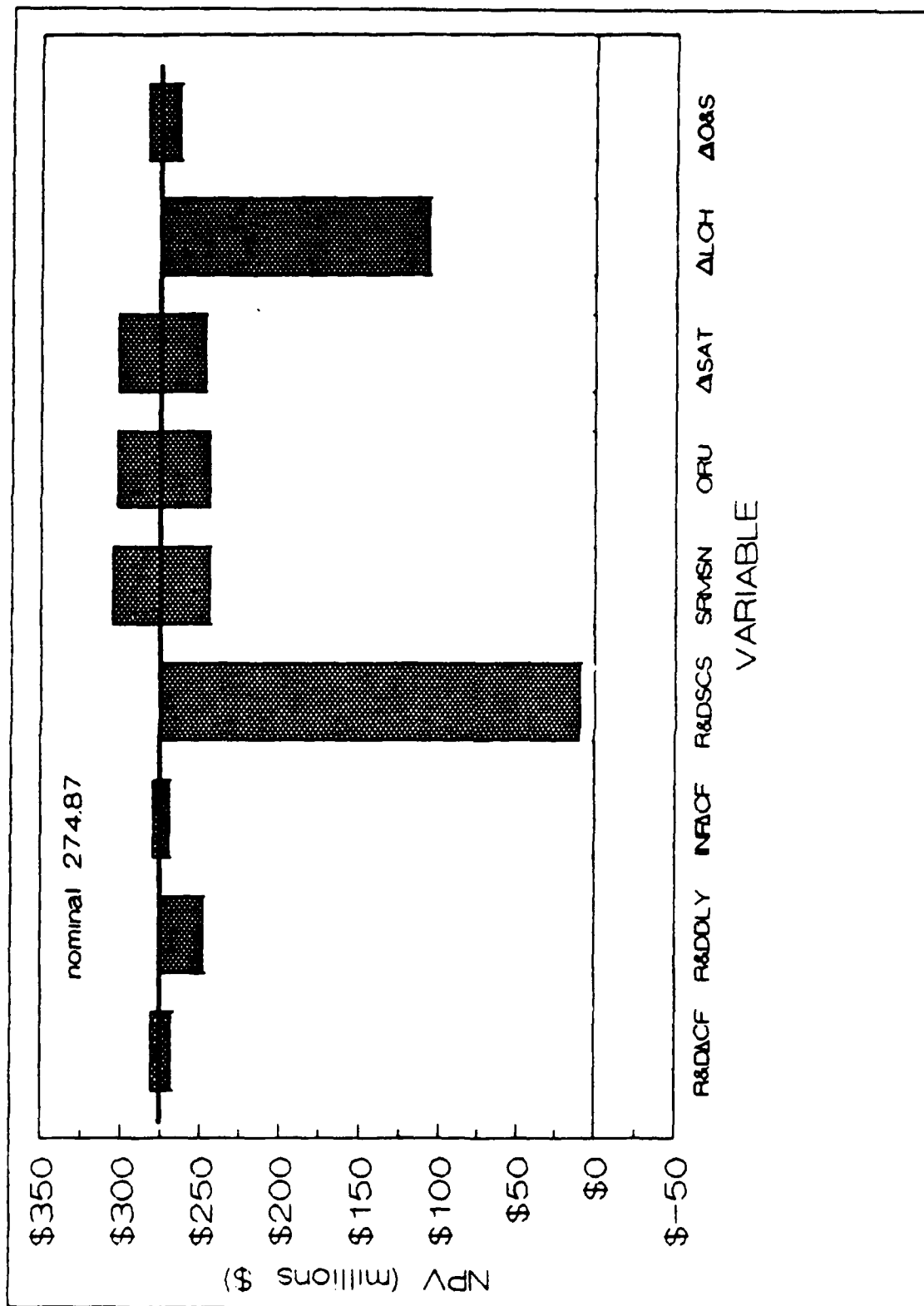


Figure 21. S/R Alternative--Deterministic Sensitivity Analysis

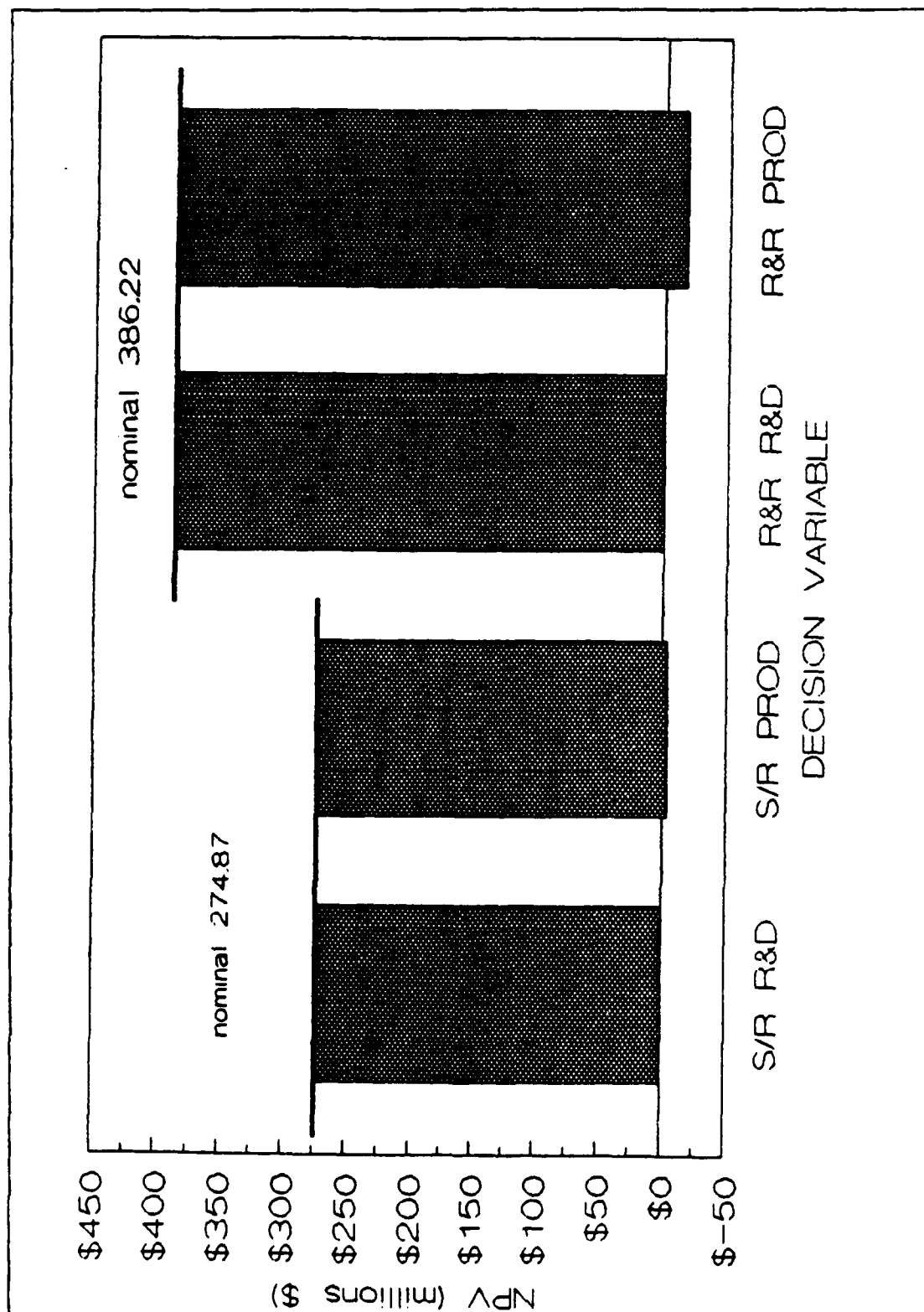


Figure 22. Decision Variables--Deterministic Sensitivity Analysis

The uncertainty in the successful outcome of an alternative's R&D effort, R&D SCS, and the additional launch cost,  $\Delta LCH\ COST$ , have the greatest effect on value. Naturally, the success or failure of the R&D effort, greatly affects value. Failure causes the loss of the additional funds used to develop extended design life and success would allow the nominal NPV to be reached. The nominal and high (low cost) settings for the additional launch costs were the same and so the nominal value is the highest attributable to  $\Delta LCH\ COST$ . Its low effect on value reflects the possibility of having to launch each satellite on its own expendable launch vehicle. The uncertainty of the last two variables is also important.

The nominal and high (no delay) settings for the possible stretchout of the R&D phase, R&D DLY, were also the same. Once again, the high NPV is the nominal. The low value is a result of a possible one year delay. The case of additional satellite costs,  $\Delta SAT\ COST$ , is different. The benefit of requiring fewer overall satellites is offset by the higher cost range of the increased reliability (R&R) satellite.

In the S/R alternative, the same variables have the same general effect on value. In addition, the additional infrastructure cost ( $INF\Delta CF$ ) has little effect on value. Its delta value is 10.67 and is less than R&D  $\Delta CF$ 's 12.55 million dollars. Setting both at their nominal values could make a difference in the final comparison. Only  $INF\Delta CF$  was set at its nominal setting after determining that no preferential dependence existed.

One would expect that the decrease in total number of satellites (from 25 in the expendable program to 7 in the S/R program) would cause a much greater change in value. The benefit of fewer required satellites was largely offset by their increased cost and the nominal cost of the orbit



replaceable units, ORUs, that are required. Both decision variables are also important in both alternatives.

The R&D and production decisions have identical max swings within the same alternative. In either alternative, the nominal NPV can be attained. The low swings are, of course, different. If the decision is made not to enter R&D with an alternative, there is no loss. The decision not to produce would result in the loss of the R&D funds.

The key uncertainties have been identified for each alternative. One variable in each alternative has been set to its nominal setting with the determination that this will not alter the choice between alternatives. This simplified the probabilistic phase by eliminating consideration of the uncertainty in those two variables. In the probabilistic phase, the effect of uncertainty is included in the determination of an alternative's value. The deterministic phase only produces the maximum and minimum swings in value possible. The probabilistic phase includes the likelihood of those swings.

## VI. Probabilistic and Information Phases

### Overview

The deterministic phase distinguished the key random variables for each alternative in the hypothetical scenario. One random variable was set to its nominal value in each alternative. This was done on the basis of their overall possible contribution to the value of an alternative. Regardless of their probability distributions, these variables would not be decisive to the decision.

In the probabilistic phase, the probability distributions were encoded for the remaining random variables. These probability distributions and the associated outcome values allow the model to be solved. The completed model also provided further information on the variables as they relate to the scenario.

The decision analysis process is iterative. With the insights provided by the initial problem solution, the model is reevaluated. The first pass at the problem points to those variables where more information may be beneficial. Random variables initially thought critical may prove to have no effect on the decision. In this way, the model is further tailored for its application to a specific scenario.

The decision analysis cycle is completed in this chapter for the hypothetical scenario presented in Chapter 5. The results of the first pass at the problem and several examples of the information phase are presented.

### Probabilistic Phase

The first task of the probabilistic phase is to encode the probability distributions for the remaining random variables (aleatory variables).

The scenario's decision maker was interviewed and the distributions encoded. The encoding was accomplished using a series of lotteries involving a probability wheel and judgements on the value an aleatory variable could assume. Each lottery outcome defined a point on the aleatory variable's cumulative distribution function.

The decision maker was consistent for all assessments. Values were randomly picked and lotteries conducted on both a "greater than" and "less than" basis for each variable. Figure 23 is a sample graph from the interview. The remaining graphs are in Appendix E.

The aleatory variables' cumulative distribution functions were then discretized for use in solving the model. These discrete approximations are listed on the appropriate graphs and listed in Table 5. Low, medium, and high categories in the table refer to the effect of that setting of the variable on an alternative's value. For example, a 4.8% increase in satellite cost, the low setting, would represent a higher value of the service/repair (S/R) alternative compared to the low setting of 14%.

The spreadsheets developed with the model provided the outcome values for every combination of aleatory variables and those variables set to their nominal settings. For example, the schedule of missions was programmed into the ESCM.WKQ spreadsheet for the enhanced expendable satellite (increased reliability and/or redundancy for increased design life, the R&R alternative). The variables were then entered in the spreadsheet. The result was a net present value for that combination of variables. The aleatory variables were varied until a net present value was returned for each possible combination.

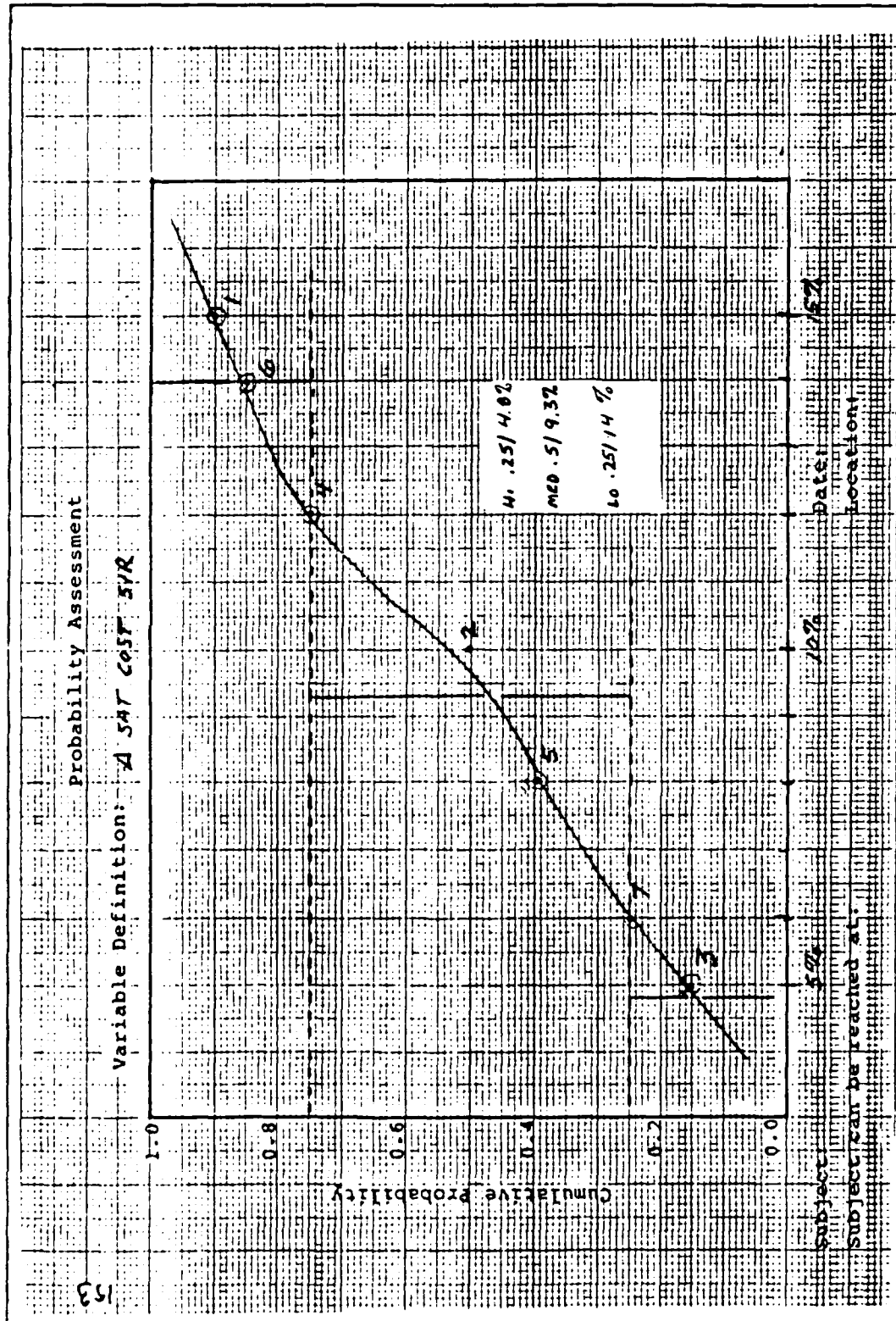


Figure 23. Probability Encoding Worksheet, S/R Alternative,  $\Delta$ SAT COST

Table 4. Aleatory Variable Ranges and Probabilities

| <u>S/R Alternative</u> |               |             | <u>Variable</u>                   | <u>R&amp;R Alternative</u> |               |             |
|------------------------|---------------|-------------|-----------------------------------|----------------------------|---------------|-------------|
| <u>Low</u>             | <u>Medium</u> | <u>High</u> |                                   | <u>Low</u>                 | <u>Medium</u> | <u>High</u> |
| 1.0                    | 1.0           | 0.0         | R&D DLY<br>(years)                | 1.0                        | 1.0           | 0.0         |
| 0.1                    | 0.1           | 0.8         | Probability                       | 0.1                        | 0.1           | 0.8         |
| fail                   |               | success     | R&D SCS                           | fail                       |               | success     |
| 0.05                   |               | 0.95        | Probability                       | 0.1                        |               | 0.90        |
| 10.2%                  | 5.3%          | 2.0%        | R&D $\Delta$ CF<br>(% increase)   | Nominal                    |               |             |
| 0.25                   | 0.5           | 0.25        | Probability                       |                            |               |             |
| 101.0%                 |               | 1.0%        | $\Delta$ LCH COST<br>(% increase) | 100.3%                     |               | 0.3%        |
| 0.05                   |               | 0.95        | Probability                       | 0.98                       |               | 0.02        |
| 14.0%                  | 9.3%          | 4.8%        | $\Delta$ SAT COST<br>(% increase) | 31.4%                      | 23.6%         | 16.4%       |
| 0.25                   | 0.50          | 0.25        | Probability                       | 0.25                       | 0.50          | 0.25        |
| 13.8%                  | 9.7%          | 5.9%        | ORU COST<br>(% of SAT COST)       |                            | N/A           |             |
| 0.25                   | 0.50          | 0.25        | Probability                       |                            |               |             |
| 4.25                   | 2.25          | 0.50        | O&S COST<br>(millions \$/yr)      |                            | N/A           |             |
| 0.25                   | 0.50          | 0.25        | Probability                       |                            |               |             |
| 25.75%                 | 15.75%        | 10.0%       | S/R MSN COST<br>(% increase)      |                            | N/A           |             |
| 0.25                   | 0.50          | 0.25        | Probability                       |                            |               |             |

A simplified representation of the scenario is presented in Figure 24. The figure is simplified in several ways. The tree for the S/R alternative is not included--only its expected value. All examples are based on the the simplified representation. The examples are based on the R&R alternative's complete tree but the processes discussed also apply to the S/R alternative's tree. Although the complete tree structure for the R&R alternative is presented, each variable's complete description is only

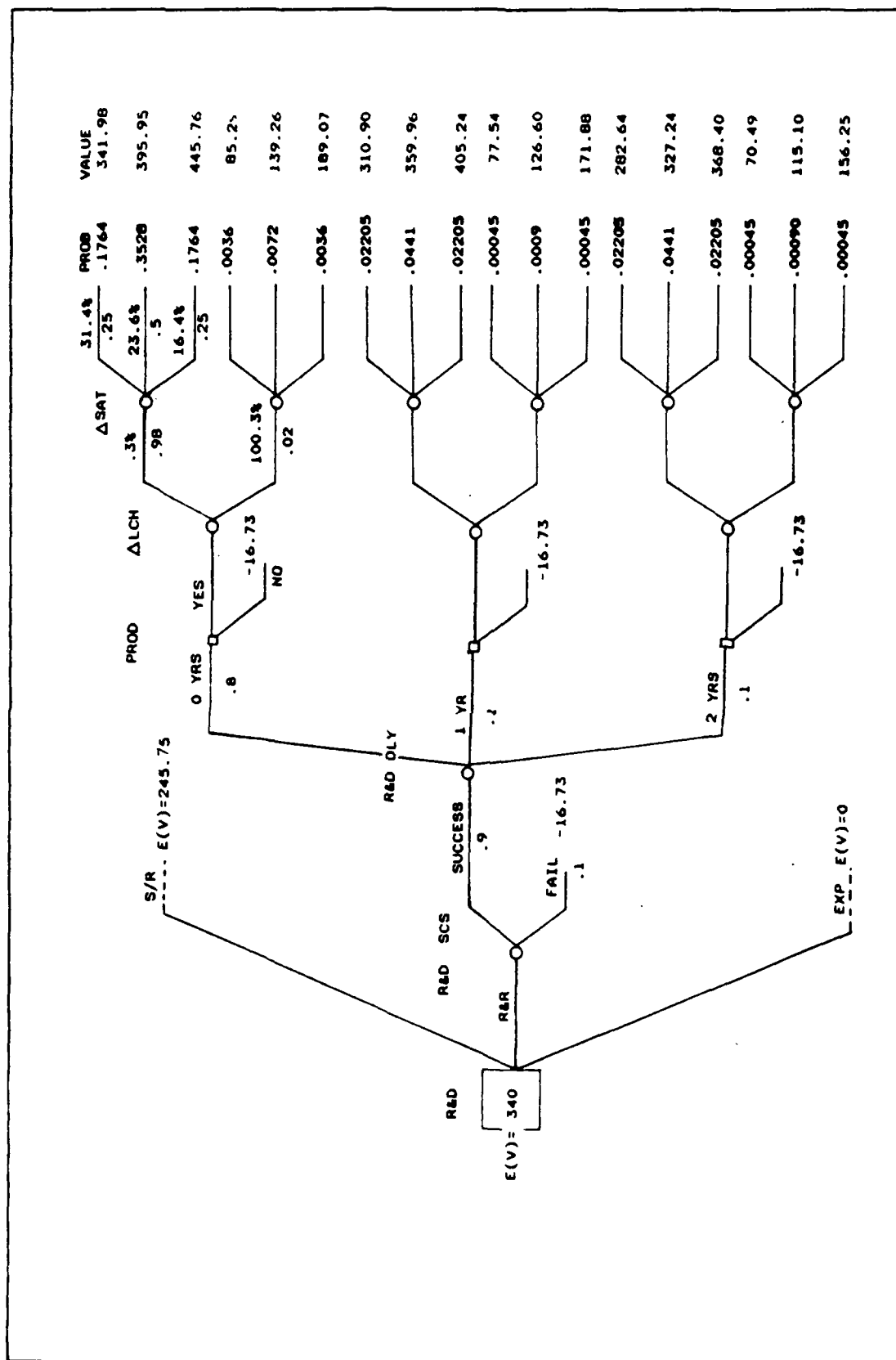


Figure 24. Simplified Scenario Problem Tree

depicted once. Recognize that, for instance,  $\Delta LCH$ , has two identical trees directly below the completed tree. All three have the same outcomes and probabilities.

The probability column, PROB, lists the probabilities associated with the possible paths through the R&R alternative. The value column lists the net present value for each of those paths. For example, the combination of entering R&D with an R&R satellite design strategy, successfully developing it, with no delay, producing it with low launch costs (.3%) and high satellite costs (31.4%) is .1764. The net present value of that combination is 341.98 million dollars.

The combination of all possible outcome values and the probabilities of those values define a distribution function of the value of an alternative (21:36). The worth lottery graphically displays the comparison of the two alternatives and the default alternative's (S/R, R&R, and expendable satellites) value distributions. Figure 25 is the worth lottery for the scenario.

The worth lottery for the R&R alternative was constructed by sorting the values, together with their probabilities, in decreasing order of value. The curve for the R&R alternative's worth lottery was then constructed point-by-point. The first point is defined by the fact that the probability equals one of returning a value of at least -16.73 million dollars. The second point is defined by the probability of .9, (1-(.1 of a -16.73 million-dollar value)). This indicates that the R&R alternative has a .9 probability of a return greater than -16.73 million dollars. The process was continued until the highest value, 445.76 million dollars, for the R&R alternative was reached. There is a zero probability of exceeding

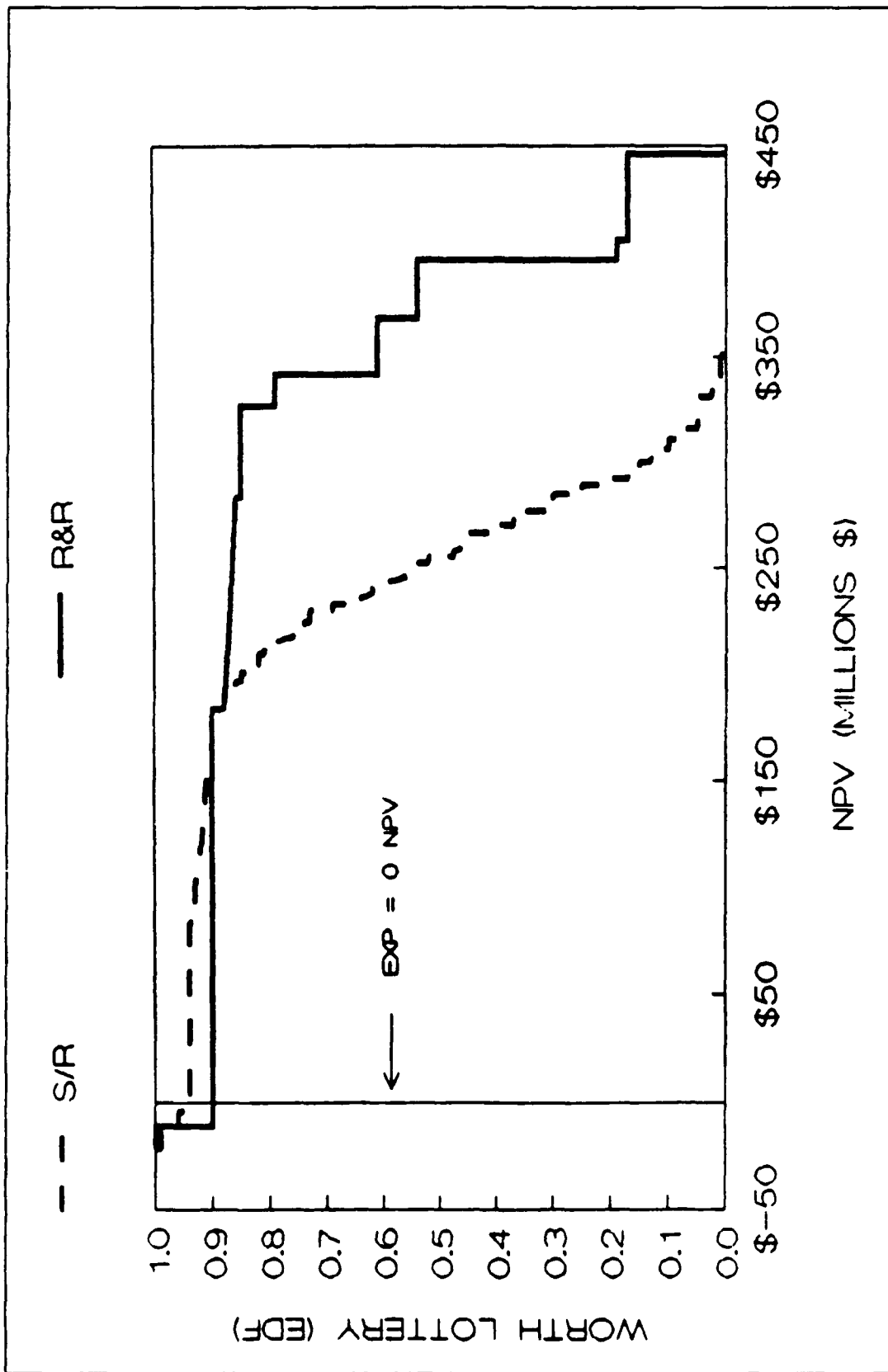


Figure 25. Worth Lottery



445.76 million dollars. This defines the last point of the alternative's worth lottery. The same process was followed for the S/R alternative and the default alternative has zero value. Several conclusions are possible after examining the worth lottery of the scenario.

Both alternative's virtually dominated the expendable satellite default alternative stochastically. In turn, the R&R alternative almost dominated the S/R alternative stochastically. The scenario's decision maker was risk neutral. In any case, he would have to be extremely risk averse not to select the R&R alternative. The R&R alternative has a probability of .9 of exceeding a net present value of zero--the expendable satellite alternative's  $E(V)$ . It also has a .6 probability of exceeding 350 million dollars--the maximum possible value of the S/R alternative.

The S/R alternative has an expected value of 245.75 million dollars (net present value) and the R&R alternative's expected value is 340 million dollars. Recall that the intangible benefits of the S/R alternative had not been included. The probability-versus-value graph presents a method of identifying the required intangible benefit and probability to decide in favor of the S/R alternative. The probability-versus-value graph is depicted in Figure 26.

The net difference in expected values between the S/R and R&R alternatives is 94.25 million dollars. The curve in Figure 26 defines the combination of probability and net present value for the intangible benefits which equalizes the expected values of the S/R and R&R alternatives. In the S/R alternative, the intangible benefit can be realized if the service/repair satellite is successfully developed and produced. Solving the S/R alternative's tree showed that if it was

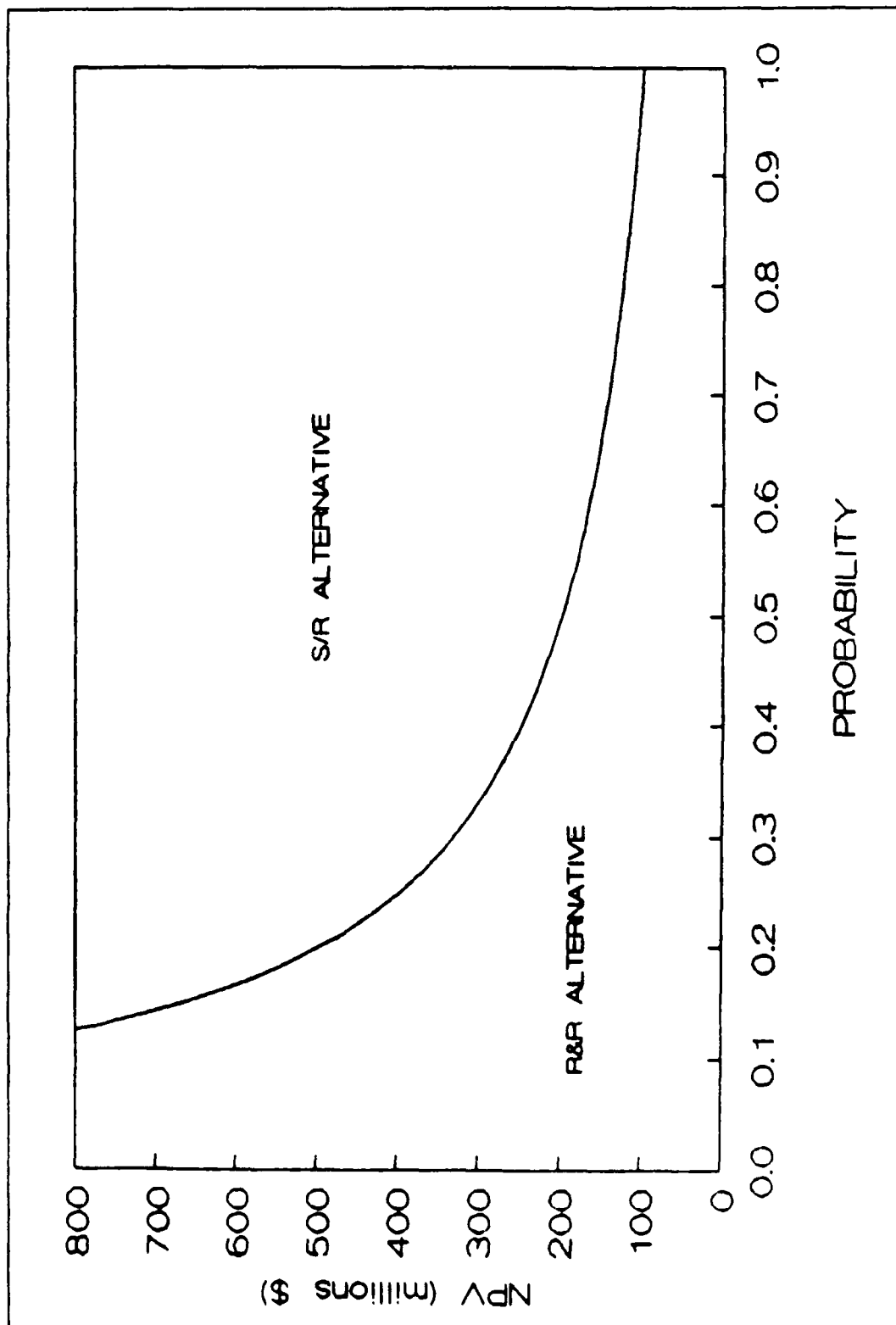


Figure 26. Probability-versus-Value, S/R Alternative, Intangible Benefits

successfully developed, it would be produced. The probability of successful R&D is .95. The equation for the curve was solved as follows: Let  $Y$ =intangible benefit and let  $X$ = probability of receiving the benefit. The  $E(V)$  of the benefit is therefore  $YX(.95)$ . For the curve,  $YX(.95)=94.25$  million dollars. The equation of the curve is  $Y=94.25/ (.95X)$ .

The decision maker need not have a precise judgement on the probability and value associated with the intangible benefits to use the graph. For instance, if the decision maker feels that the S/R alternative has a greater than 70% likelihood of exceeding a 200 million dollar net present value, he would decide in favor of the S/R alternative. The evaluation of the model serves as a starting point for evaluating the need and value of additional information on the aleatory variables.

#### Information Phase

Gathering further information entails incurring the additional cost of gathering that information. Additional information may serve to decrease the uncertainty and risk involved in decision making. The decision maker would naturally desire to remove as much uncertainty as possible. However, he must determine if the information is needed and its value to the decision.

The limit on value of information for an aleatory variable is the value placed on perfect information. This limit is defined by the amount that having perfect information for an aleatory variable changes the expected value of the decision. There is very little uncertainty in the scenario that would affect the decision because of the virtual stochastic dominance of the R&R alternative.

The decision maker should not seek further information on the possible delays or satellite costs associated with the R&R alternative. Even with perfect information, the decision would not change. These two variables have an expected value of perfect information (EVPI) of zero. The other two aleatory variables for the R&R alternative are a different matter.

With perfect information on the additional launch costs associated with the R&R alternative, the expected value of the decision increases .2 million dollars (EVPI=.2 million dollars). This is caused by the fact that if the decision maker knew that the launch costs would be 100.3% greater than the expendable satellite case, he would switch to the S/R alternative. Figure 27 is Figure 24 converted to compute the EVPI for the delta launch costs of the R&R satellite. The EVPI for the variable reflecting the likelihood of success, R&D SCS, for the R&R alternative's R&D effort is 26 million dollars. These values are the absolute limits for perfect information. In reality, perfect information is rarely available. The value of less-than-perfect information (EVI) can also be determined.

EVI is based on the confidence the decision maker has on the source of additional information. Consider a consultant hired to provide additional information on the prospects for success of the R&R alternative's R&D effort. The decision maker determines that the consultant will predict success or failure correctly 95% of the time. The consultant's report increases the expected value by 19.5 million dollars. This represents the theoretical limit for the cost of the report. A successful prediction rate of 90% returns the same expected value. The decision maker would have the same expected value with or without the report. The EVI of this report is zero.

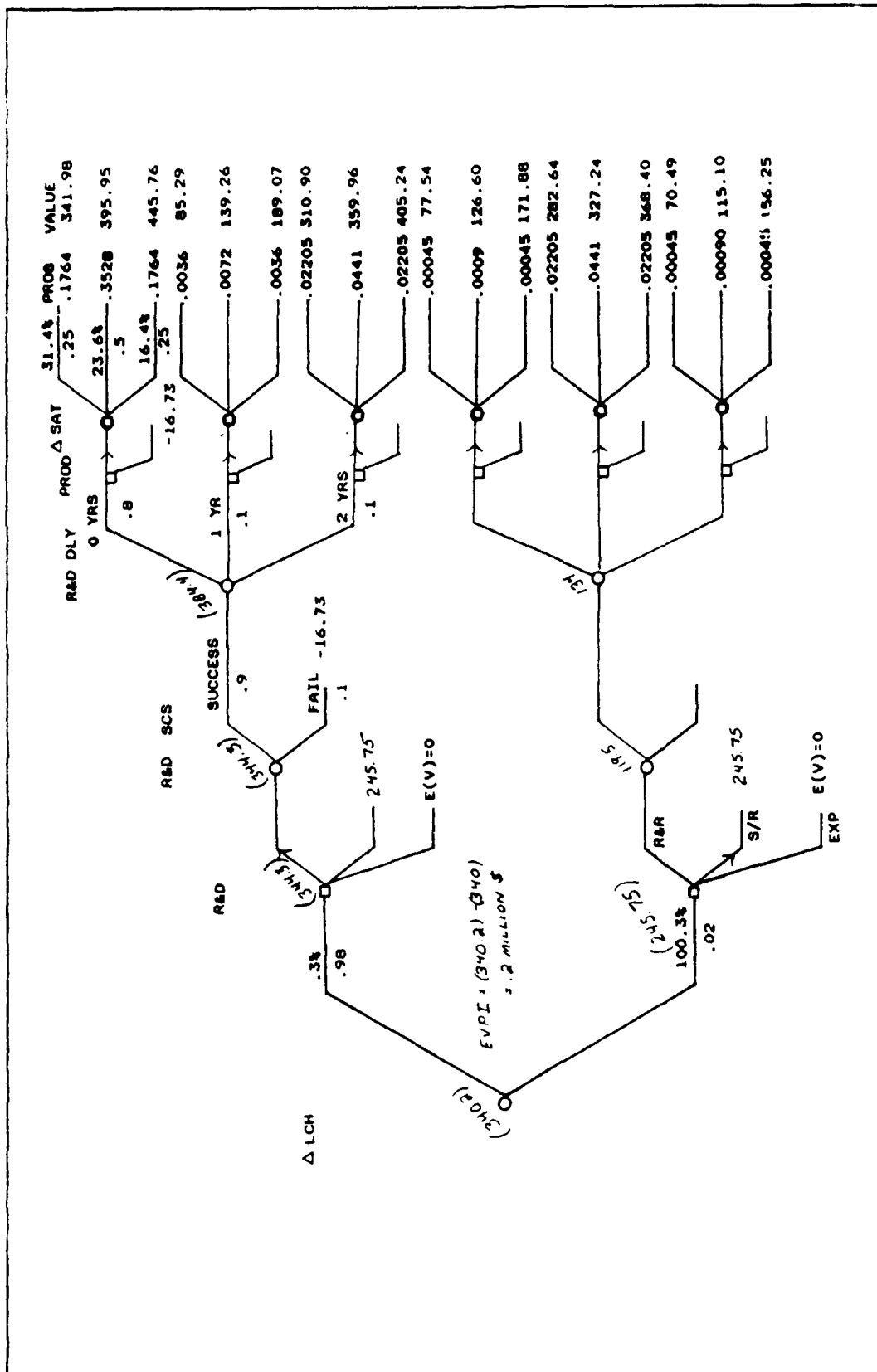


Figure 27. Scenario Problem Tree, EVI, R&R ΔLCH COST

The decision maker may also be concerned that some of the variable ranges may be incorrect. A sensitivity analysis can also be performed to consider that possibility. The additional launch costs were judged to range from .3 to 100.3% in the R&R alternative. With the same cumulative probability distribution, the range would have to increase to 36.1 to 136.1% before the decision would be affected. The additional satellite costs would have to increase from the 16.4% to 31.4% range up to a 31.4% to 46.4% range to change the decision. Finally, the likelihood of successfully developing the increased design life would have to decrease from 90% to 66%. Each of these is a single variable consideration. Combinations of changes or changes in the cumulative distribution functions require reentry into the spreadsheet and reevaluation.

In this chapter, the probabilistic and information phases of the decision analysis cycle were applied to the scenario. By encoding the distributions for the aleatory variables and then evaluating the worth lottery, a preliminary evaluation of the alternatives was performed. The model was solved without the intangible benefits of the S/R alternative included. The probability-versus-value graph was developed for considering the intangible benefits.

Examples of information that are available from the model were presented. The model, as applied to this scenario, could be further refined. Several of the aleatory variables for this scenario could be set to their nominal settings with no loss in resolving decision. Further information could be gathered on the remaining aleatory variables based on the EVPI and EVI calculations.

The pilot decision analysis model and its application to a hypothetical

scenario were intended as a demonstration of decision analysis' utility in strategic decision making. The conclusions of this exercise are presented in the following chapter.

## VII. Conclusion

Satellites provide important capabilities for our military operations. We have become increasingly dependent upon satellite resources. The costs of providing those resources is considerable. Conducting on-orbit service/repair or retrieval of satellites have been advanced as means of providing satellite resources at a lower cost. A program manager must assess the potential benefit of adopting an on-orbit service/repair or retrieval design strategy for a satellite program. The decision as to which design strategy should be pursued is well-suited for the decision analysis methodology. It involves risk, uncertainty, and complexity. This thesis demonstrated the application of the decision analysis methodology to this decision.

A pilot decision analysis model for a general-case satellite program was developed. The model's influence diagrams precisely structured the key variables, alternatives and their relationships within the context of the decision. Uncertainty, risk, and value preferences were explicitly captured in the model's structure.

The model allows a direct comparison of the relative benefits of alternative satellite-design strategies when compared to the expendable-satellite design strategy. Six alternative-specific spreadsheets were designed based on the model's structure. These spreadsheets calculate the comparative net benefit (NPV) for three alternative design strategies. The spreadsheets proved to be invaluable tools that greatly aided the analysis.

The pilot model and its utility were demonstrated by applying the model to a hypothetical satellite program. The application also presented the strongpoints of the decision analysis methodology. The deterministic



sensitivity analysis identified the key uncertainties, those that will affect the decision. They were included in the decision analysis by encoding the decision maker's judgements of these uncertainties. In this way, the decision accounts for the value as well as the likelihood of the benefits.

The ability of decision analysis to provide the value of information to the decision was demonstrated by several examples based on the hypothetical program. Other factors, such as the intangible benefits of an alternative, not normally included in cost analyses, were also included in the sample analysis. In this way, the final decision is made based upon all of the important aspects of the problem.

"Although an organization can achieve ultimate success only by enjoying favorable outcomes, it can control only the quality of its decisions" (6:55). Decision analysis provides a means to control the quality of decision making. This study demonstrated the utility of decision analysis as a methodology for structuring and analyzing the on-orbit service/repair or retrieval decision. The pilot decision analysis model and its spreadsheet representations serve as a foundation for the application of decision analysis to the on-orbit service/repair decision.

## Appendix A. Influence Diagrams

Influence diagrams graphically show the structure of a problem. The key variables and decisions are depicted as nodes of the influence diagram. The flow of information and the influence (dependency) is shown by the arcs connecting nodes. Random variables, uncertainties, are represented by circles. Deterministic variables, the variable's value is known given its arguments, is represented by a double circle and decisions by squares. A diamond indicates the value variable (1:1-2)

A simple example shows the influence diagram's use. Scenario: A contractor's payment from a communications company depends on when he can place the company's satellite into orbit. The contractor knows that the comm satellite weighs 10,000 lbs. and his decision is which of two eligible boosters he should choose (A or B) or he could decline the contract. Type A costs 100 million dollars and has a probability of a successful launch of .95. Type B costs 75 million dollars and has a probability of a successful launch of .85. The contractor is responsible for the cost of the booster. If he delivers the satellite on-orbit within 1 year, he will be paid 200 million dollars at the one-year point; between 1 and 2 years, he receives 150 million dollars at the two-year point; after 2 years, he gets 125 million dollars at the three-year point. The contractor knows that he will deliver the satellite on-orbit no later than the three-year point. The contractor will only make one launch attempt and the uncertainty is when he will be able to launch in the three year window.

The value the decision maker has for the outcome of the contract is the NPV of the contract minus the booster price which he buys upfront. The contractor uses a 10% discount rate for NPV calculations. Figure 28 shows

the influence diagram for this scenario. The satellite weight (SAT WT) is known prior to the decision. Value is dependent on the probability of launch success (LS) which in turn depends on which booster is chosen. Value is also dependent on the discount rate ( $i^*$ ) and when the contract is fulfilled (CON). The cumulative distribution function (CDF) for the key uncertainty, CON, is represented by three discrete probabilities: .5 for one year or less, .25 for between one and two years, and .25 for greater than two years. The CDF was constructed through an interview with the contractor and represents his best information on when he can meet the contract. Con is independent of the booster selection (no arc from the decision to CON). Any delays will be a result of the contractor's operation and not the time the booster is delivered. Both boosters will be delivered six months after the order is placed.

Figure 29 represents the tree structure derived from the influence diagram and its solution. The contractor is risk neutral and will take the highest expected value. The tree is rolled back and the expected value  $E(V)$  calculated. In this case, booster B is the choice. It's lower price more than offsets its lower probability of successful launch.

Several collective variables were used in the chapter 3 model and then decomposed to show further detail. A full influence diagram with all the required arcs and variables would be "busy" to say the least. For this reason, the complete model uses collective variables. Arcs between collective variables indicates an influence exists between some or all of one collective variable and the other's decomposed variables. The text describes these relationships.

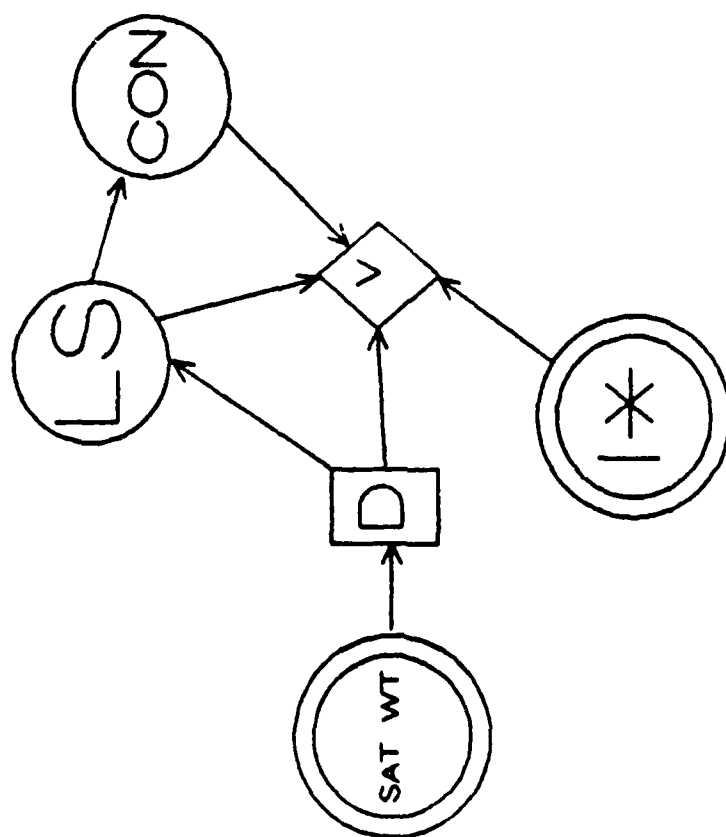


Figure 28. Sample Influence Diagram

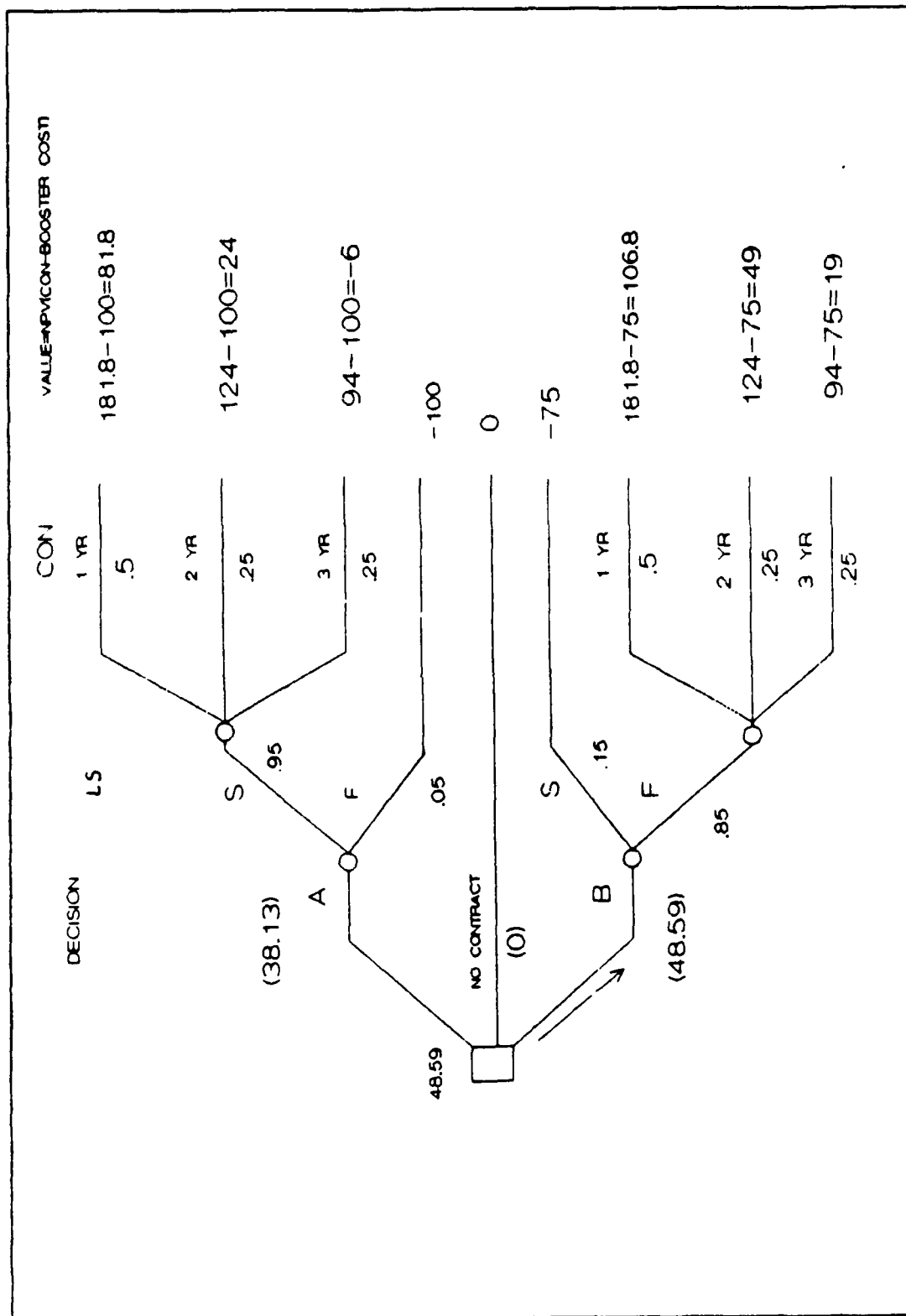


Figure 29. Sample Decision Tree

## Appendix B. Spreadsheet Documentation

The documentation for the six spreadsheets developed for the pilot decision analysis model are included.

ALTERNATIVE SPACECRAFT DESIGN STRATEGIES  
SOFTWARE DOCUMENTATION

I. INTRODUCTION

General

The floppy disks contain six spreadsheet files:

RRRM.WKQ  
RRRA.WKQ  
SERRA.WKQ  
SERRM.WKQ  
ESCA.WKQ  
ESCM.WKQ

RRRM.WKQ and RRRA.WKQ are for analyzing the retrieve, refurbish, and relaunch strategy. ESCM.WKQ and ESCA.WKQ are for the enhanced-expendable strategy and SERRA.WKQ and SERRM.WKQ are for the servicing and/or repair strategy. An A at the end of a file name indicates that the program will compute results automatically after the variable values have been entered. An M indicates that, in addition, some manual data entry is required prior to automatic results computations. These files are ready for use with Quattro software. Quattro also has the capability to convert the files for use with other spreadsheet software.

The six spreadsheets are protected so that values may only be entered in the proper cells. All text and formulas cannot be erased in error. The protection feature can be disabled (see Quattro documentation) should alterations be desired. All programs are macro driven. The macros move the screen to the desired starting point for value entry or for viewing the output. The macro options are displayed on a menu (alt M) and may be selected at any time.

### Spreadsheet Design Philosophy

All six spreadsheets have several features in common. All variables are of two types--cost or event scheduling. Each spreadsheet combines the completed variables into an event timeline showing all scheduled missions. They then compute the associated cash flow and the derived benefit from pursuit of the modeled strategy. An important point is that the benefit is computed from a comparison of the modeled strategy against a baseline expendable spacecraft strategy. A Net Present Value (NPV) of the prospective benefit and cost cash flows is computed and an overall NPV for the benefit is presented. The present time used is the year before the prospective R&D phase is to begin. This represents the perspective of a manager examining possible strategies that may be pursued for the spacecraft. The spreadsheets are intended to answer the basic question involved in pursuing any new design concept--do the anticipated future benefits return enough to justify increased spending upfront to develop the concept?

Any of the six spreadsheets can be used for an entire spacecraft program. Automatic versions have limitations on the total number of spacecraft that can be modeled due to computer RAM considerations. Manual versions can handle a program of an unlimited number of spacecraft. Both types have program duration limitations. Each version is detailed with specific variable definitions, assumptions, and notes and tips for modeling likely situations.



AD-A203 830

ASSESSING POTENTIAL BENEFITS FOR SERVICE/REPAIR AND

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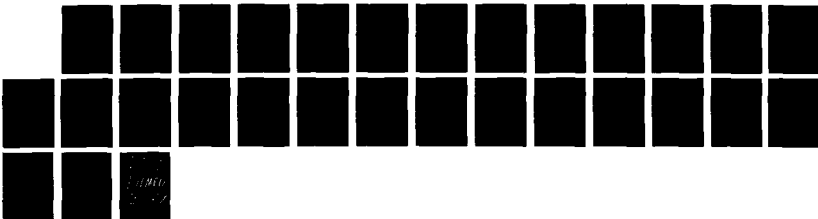
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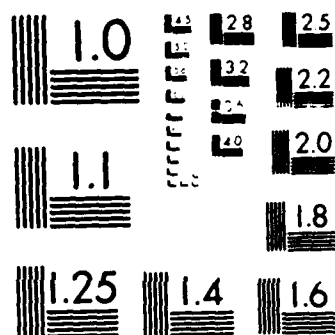
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MICROCOPY RESOLUTION TEST CHART  
NATIONAL BUREAU OF STANDARDS 1963-A

## II. SPREADSHEET DETAILS

### RETRIEVE, REFURBISH, RELAUNCH (RRR) STRATEGY

The manual and automatic versions of this strategy compare a strategy where on orbit spacecraft are retrieved, refurbished and relaunched instead of launching a new expendable spacecraft. The central issue is whether the savings involved in not having to buy a new spacecraft offsets the additional costs associated with designing a spacecraft to be retrievable, any additional launch, procurement, operational and support costs, refurbishment costs, and the retrieval mission itself. For these reasons Benefit is defined as: (\$ value of expendable spacecraft)-(additional R&D \$ vis-a-vis expendable)-(additional infrastructure \$)-(additional launch \$ both for initial and all relaunches)-(additional O&S \$)-(additional spacecraft \$)-(refurbishment \$).

#### Variable Definitions

i\*- discount rate for time-value-of-money computations. Enter as decimal value vice a percentage (e.g. 5% entered as .05)

R&D PHASE LENGTH- anticipated length of the R&D phase in years for a new design. Enter a integer value; up to 10 years of cash flow can be modeled.

OPERATIONAL PHASE LENGTH- anticipated length of the operational phase in years. Enter a integer value; up to a 30 year operational phase can be modeled.

YR LAST ALLOW RRR- The last operational program year in which a retrieve, refurbish, relaunch mission may be launched.

EXP S/C COST- Dollar value in millions for the baseline expendable spacecraft.

%INCR RRR S/C- Percentage increase in cost for the RRR spacecraft; enter a decimal value. Zero may be entered.

EXP LNCH COST- Dollar value in millions for the launch costs of the expendable spacecraft. All launches are assumed to cost the same.

%INCR RRR S/C- Percentage increase in launch costs for RRR spacecraft; in decimal value. Zero may be entered.

RET MSN COST- Dollar value in millions for the retrieval mission cost.

REFURB COST AS % OF RRR S/C COST- Cost of refurbishing the RRR spacecraft expressed as a percentage of the RRR spacecraft cost.

DELTA RELAUNCH COST- Difference in the RRR spacecraft and expendable spacecraft relaunch costs in millions. Cost will depend on where the spacecraft is refurbished (ground vs space station). If the RRR relaunch is less expensive a negative value is entered.

ANN O&S COSTS EXP S/C- Annual recurring O&S costs for the operational program.

%INCR RRR O&S- The percentage increase for an RRR program; enter a decimal. RETRV'L INTERVAL- The interval in years between retrieval missions for a given spacecraft.

UPFRONT COSTS CASH FLOW- enter the dollar value in millions for the respective variable and year. Addt'l R&D are any R&D funds required to convert an expendable spacecraft to a retrievable spacecraft. Infrastructure covers all other upfront costs such as any additional construction, training, etc. required to switch the program to a RRR strategy.

S/C DEFINITION- Enter the operational phase year in which an event will occur for a given spacecraft. Enter a 31 if the event will not occur. Retrieval Failures should only be modeled in a year when a retrieval has been scheduled and likewise for launch failures. INIT LCH YEAR defines the initial launch year for the respective spacecraft. In the automatic spreadsheet all events for this spacecraft are automatically entered in the timeline based on entries in this section and the retrieval interval entry. Common sense applies. Don't schedule a launch failure after a retrieval failure for a spacecraft and vice versa (nor in the same year). Launch failure models either a failure on the pad or a failure of the spacecraft to become operational in the first year of launch. Losing a spacecraft and then having to launch a replacement can be modeled by defining another spacecraft for launch in the year in which one is lost (or any number of years later to simulate delay). In summary, the automatic spreadsheet only allows one failure per spacecraft and will not schedule any timeline events for that spacecraft after that failure. Alt B allows a review of possible scheduled events intervals for each spacecraft.

The manual version requires an entry in the spreadsheet timelines for each event and spacecraft. For example, S/C#1 is initially launched in year 1 (enter 1 in initial launch row and under year 1 column); it is retrieved in year 4 and relaunched in year 5 (enter 1 under year 4 for retrieve and 1 under year 5 for relaunch) a failed retrieval occurs in year 8 (1 is entered in failed retrieval under year 8--no value is entered for retrieval or relaunch in year 8). A failed or successful relaunch is indicated by a 1 in the RELNCH row and year column (costs are the same).

### Notes and Assumptions

1. PHASE TIMING- Normally, both versions (automatic and manual) assume that the R&D phase is initiated and completed and then the operational phase begins (i.e. there is no overlap).

2. EVENT TIMING- The automatic version schedules retrievals and relaunched in the same year. The automatic version also schedules the same retrieval interval for all defined spacecraft. In the manual version the user is free to schedule events as desired subject to the common sense restrictions already covered. The automatic version does not allow unscheduled retrieval missions should a spacecraft need retrieval prior to its normal scheduled year. The manual version must be used to model this case. The YR LAST ALLOW RRR defines a cut-off of missions before the program termination. It may not be desirable to retrieve a spacecraft within a defined time period of the end of a program.

3. CASH FLOW- The end-of-year convention is used for all NPV computations. An equal per unit/event cost is given to all similar units/events. That is, all expendable spacecraft have the same unit price, all RRR relaunched have the same cost and so on. All dollar entries must be in constant-year dollars. The manual version can model different costs for similar units/events. For example, the third and successive RRR missions are 20% cheaper--enter .8 for those missions in the event timeline.

4. DELAY MODELING- Any R&D phase stretchouts can be modeled by increasing the length of the R&D phase. If the baseline program has a 5 year R&D phase and a two-year stretchout is modeled with no additional expenditures attributable to making the RRR option--change the R&D length to 7 years and do not enter any additional R&D costs. Delays within the operational phase can only be modeled on the manual version.

5. PHASE OVERLAPS- An overlap of the R&D phase and the operational phase can also be modeled. Shorten the R&D phase definition by the number of years of overlap but still enter the correct costs for those years in the R&D timeline. For example a 10 year R&D phase with expenditures in all 10 years overlaps the operational phase by 2 years--enter 8 as the R&D phase length and keep all 10 R&D costs in the respective years.

6. MANUAL VERSION USE- The manual version is very flexible. Each spacecraft's set of entry lines in the timeline can be used to simulate a single spacecraft just as in the automatic version. The user has complete flexibility in scheduling events for that spacecraft. Alternatively, the user may use each spacecraft's set of event lines to define an orbit position within a constellation and use the line to define a series of spacecraft to fill that position throughout the program. Another option is to use a single spacecraft (s/c) set of entry lines to define the events of an entire program. To do this simply enter the total number of initial launches, retrievals, etc. for each year in the line entries for S/C#1 and a total program NPV will be computed.

7. ON-ORBIT SPARES- To launch an on-orbit spare in the automatic version, schedule an initial launch and a simultaneous launch failure. This will account for the additional costs (more expensive s/c and launch) and not schedule any retrieval missions for that s/c simulating a depowered on-orbit spare. If missions are required, treat it as any operational s/c. The manual version can handle any other schedule permutations.

#### Service and/or Repair (S/R) Strategy

The manual and automatic versions of this strategy compare a case where a program's spacecraft are designed to be serviceable and/or repairable as opposed to the current expendable designs. The benefit of not having to purchase new spacecraft and launches must offset the additional R&D, O&S, infrastructure, spacecraft, and initial launch costs associated with a C/R spacecraft as well as the S/R mission cost. The basic structure of these spreadsheets is very similar to those of the RRR strategy. Only significant differences are highlighted.

#### Variable Definitions:

1. S/C Definition- An entry is required for INT S/R MS YEAR (initial S/R mission year) for each spacecraft. To model a launch failure or failure to become operational, enter 31 and no S/R mission will be entered in the automatic version. The costs associated with the failed launch will still be incurred through entry of the initial launch year. The automatic version will also not schedule S/R missions after a programmed failure for a particular spacecraft. Otherwise, the automatic version schedules S/R missions based upon the defined first mission and the S/R interval. The initial mission definition was separately defined to allow an S/R mission within the lifetime of a spacecraft. For example, a spacecraft is given a launch year of 1 and a S/R interval of 10 with a first mission in year 5. This simulates a 10 year lifetime serviced at the midpoint of it's lifetime. With no S/R failure entered, the spacecraft is considered operational throughout the program life. Spacecraft replacement without failure, prior to the end of the program, can only be modeled in the manual version.

2. S/R MSN COST- Includes not only the cost of the mission but also the parts (orbital replacement units, ORUs) to be exchanged on the spacecraft. Any annual storage costs for ORUs should be included in the annual additional O&S costs charged to the S/R strategy.

3. MANUAL VERSION- The manual version can be used in a variety of ways just as in the RRR strategy. In addition, the S/R manual version allows the definition of 3 classes of s/c launch cost and the associated 3 S/R mission costs. These can be used to model the case where a constellation of operational spacecraft have significantly different orbits resulting in very different launch and S/R mission costs.

#### Enhanced Spacecraft Strategy

Enhanced spacecraft will use increased reliability and/or redundancy to increase lifetime. This will permit fewer overall to be purchased in a program. These two spreadsheets examine the issue of whether the additional costs to develop, procure, and launch enhanced spacecraft are offset by the reduced number of spacecraft. The spreadsheets directly compare the cash flows of an enhanced s/c strategy versus the baseline expendable s/c. The benefit of the enhanced strategy is its NPV difference when compared to the baseline.

Variable definitions are similar to those already described but in the enhanced s/c context. RAM memory limitations only allow a 25 year operational program length and automatic computations on 9 s/c (9 enhanced versus 9 baseline). The option is included of adding an additional 3 with manual timeline entries.

#### Spreadsheet 'Maps'

All variable definitions are located within cells A99 to I139.

The upper-left cell for interval computations is I99 except in the ESC spreadsheets; ESC locations are K99 and K140.

All NPV results have an upper-left cell of Y21.

All R&D timelines have an upper-left cell of AA1.

All Operational timelines have an upper-left cell of AM1.;

All Macros begin in cell V1 and Menus in A21.

Appendix C. Additional R&D Stretchout Graphs

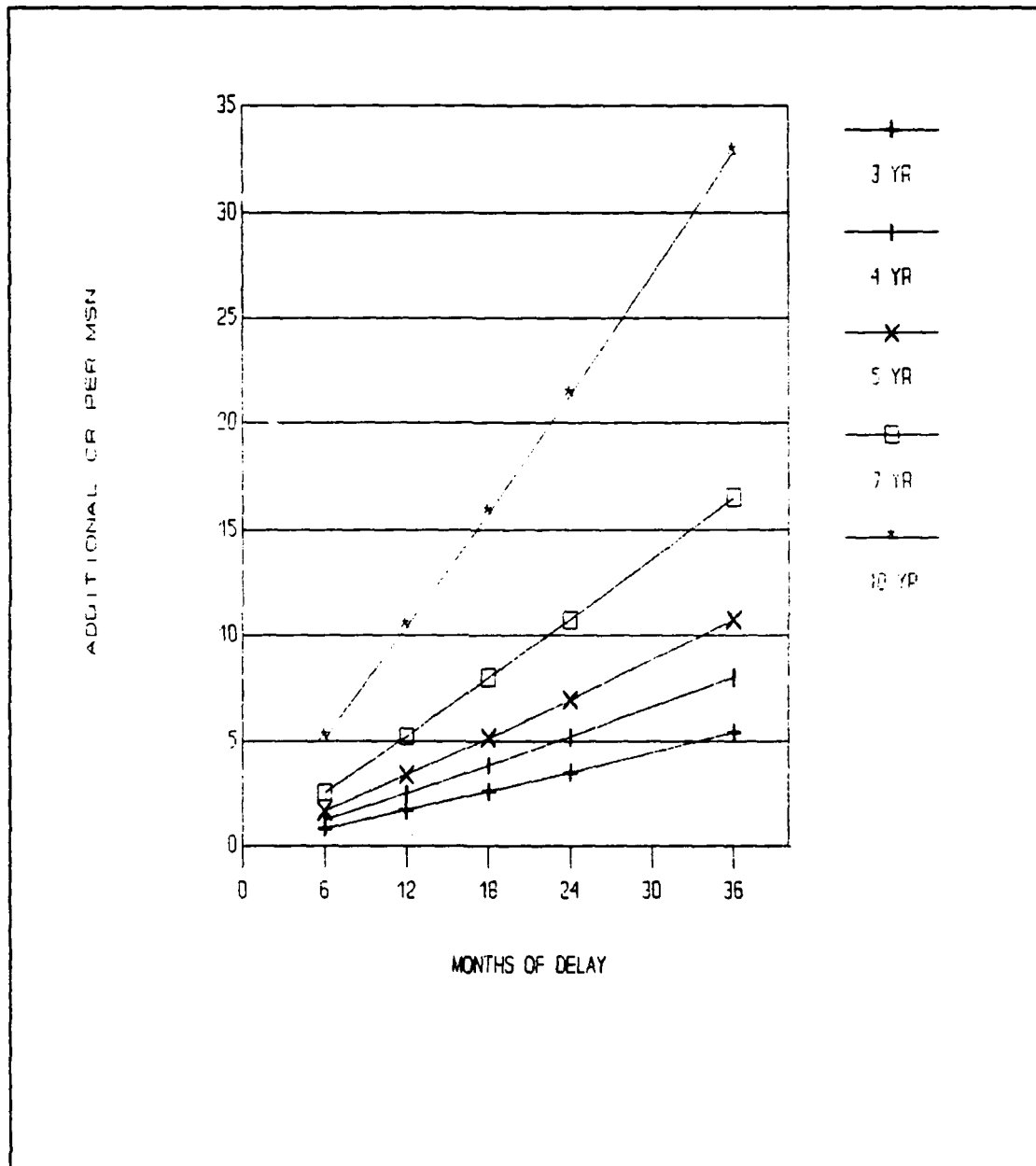


Figure 30. Additional Capital Recovery Required per Mission Due to R&D Stretchout as a % of Upfront Cost,  $i^*=5\%$ , 20-YR Operational Phase



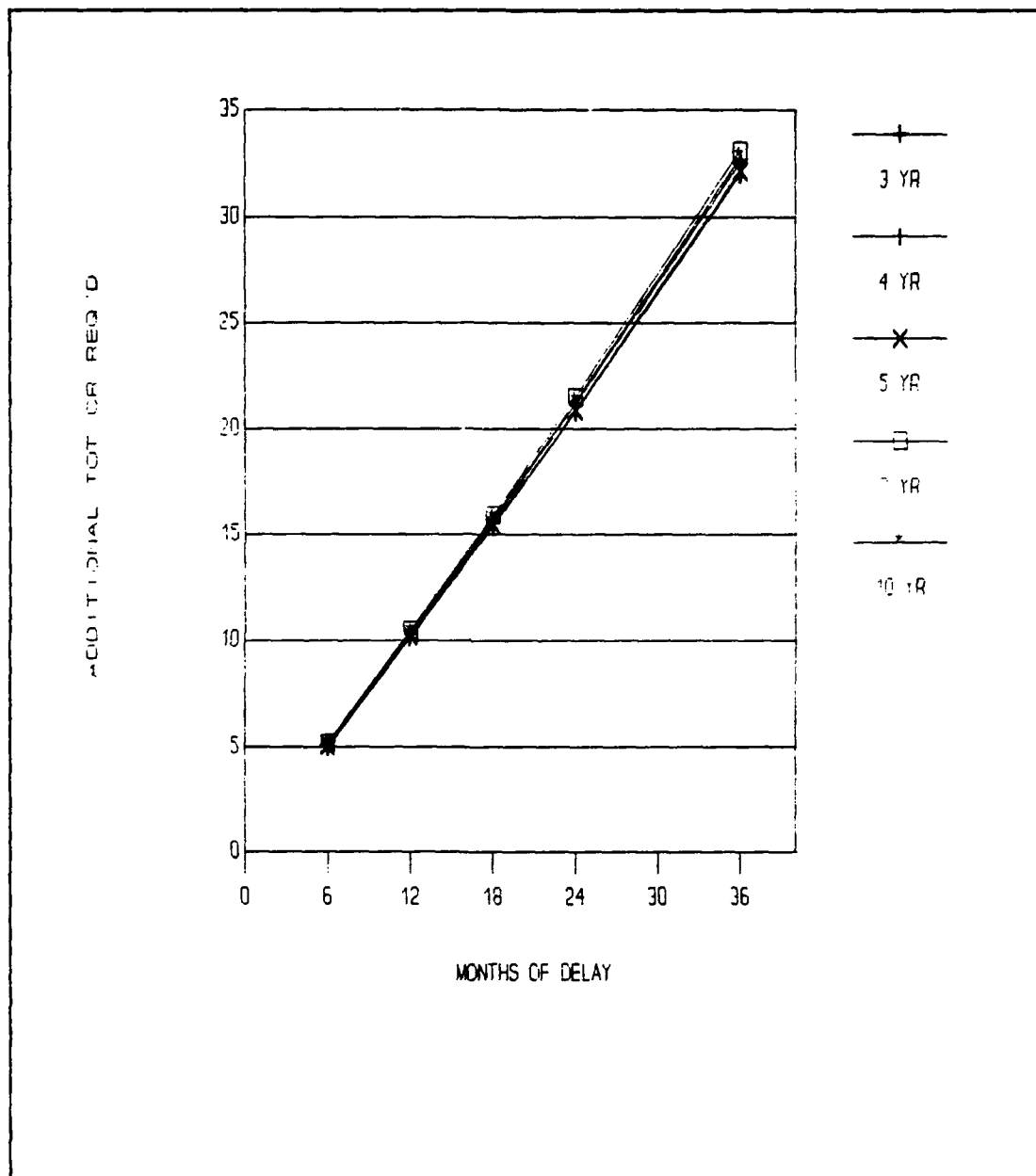


Figure 31. Additional Total Capital Recovery Required as a % of Upfront Cost Due to a R&D Stretchout,  $i^*=5\%$ , 20-YR Operational Phase

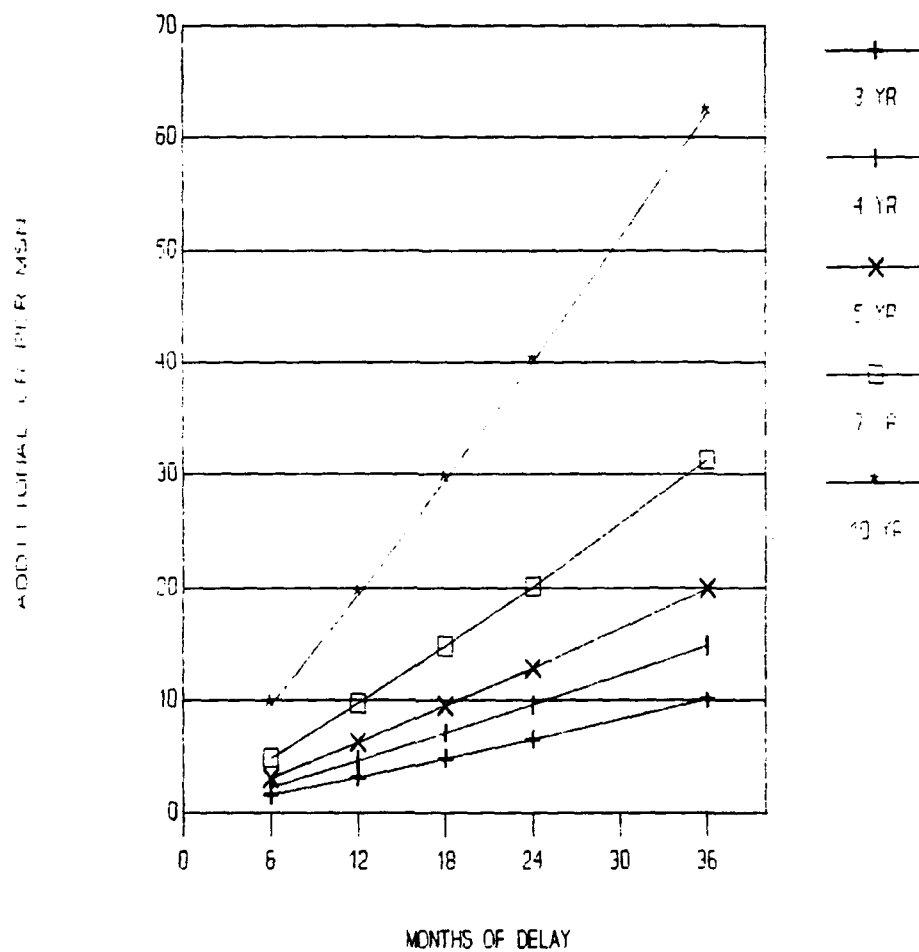


Figure 32. Additional Capital Recovery Required per Mission Due to R&D Stretchout as a % of Upfront Cost,  $i^*=7\%$ , 20 YR-Operational Phase

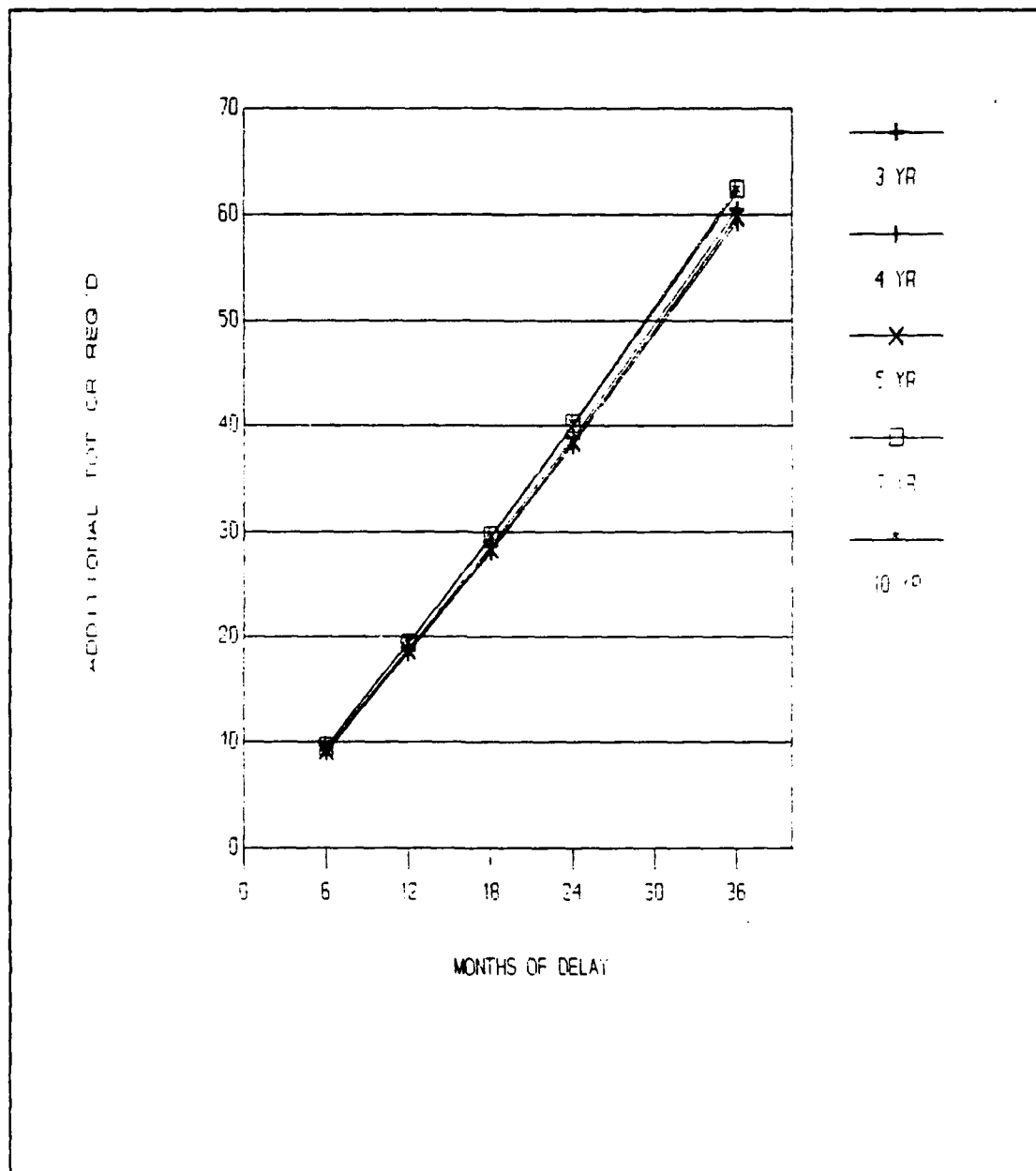


Figure 33. Additional Total Capital Recovery Required as a % of Upfront Cost Due to R&D Stretchout,  $i^*=7\%$ , 20-YR Operational Phase

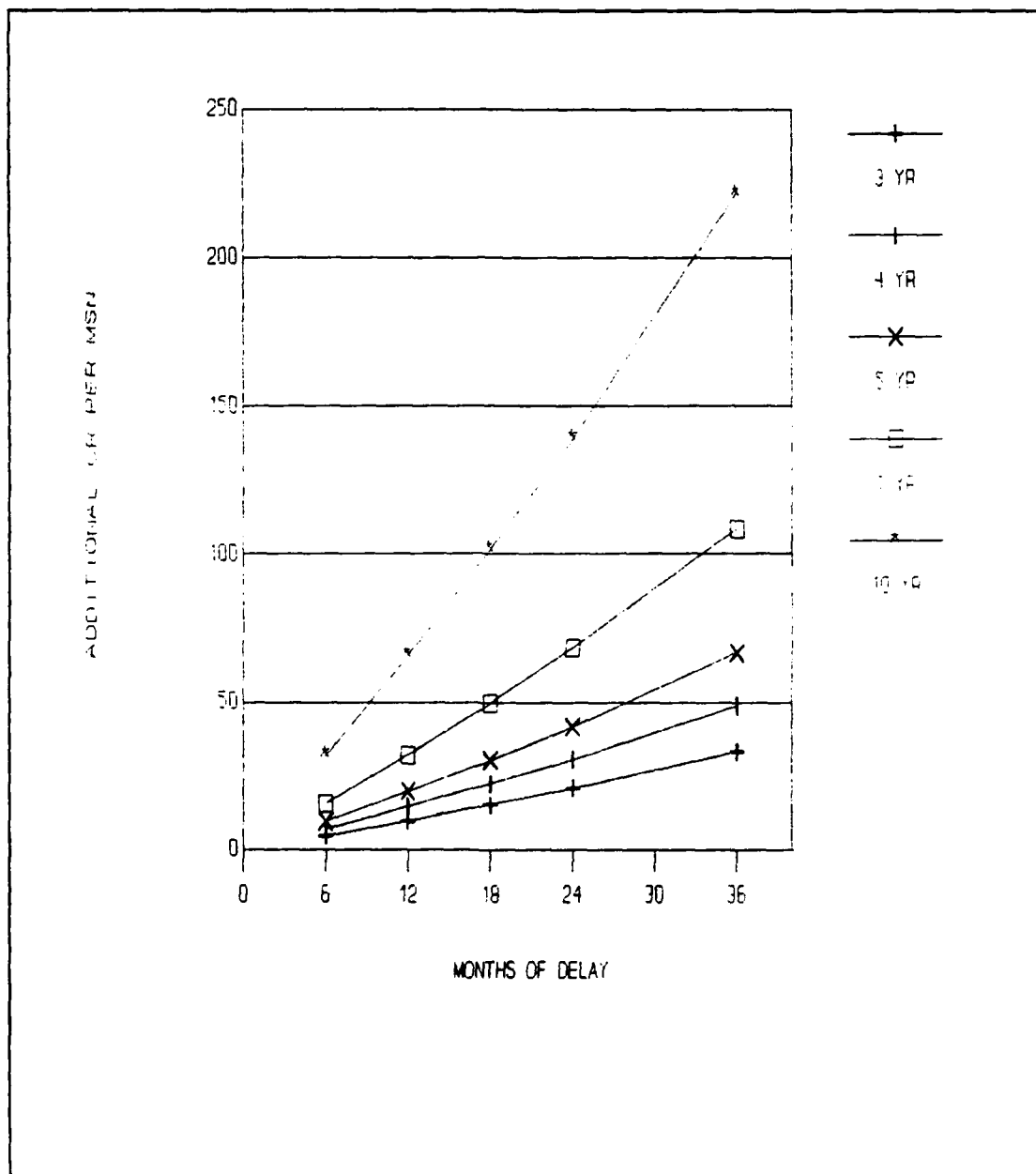


Figure 34. Additional Capital Recovery Required per Mission Due To R&D Stretchout as a % of Upfront Cost,  $i^*=12\%$ , 20-YR Operational Phase

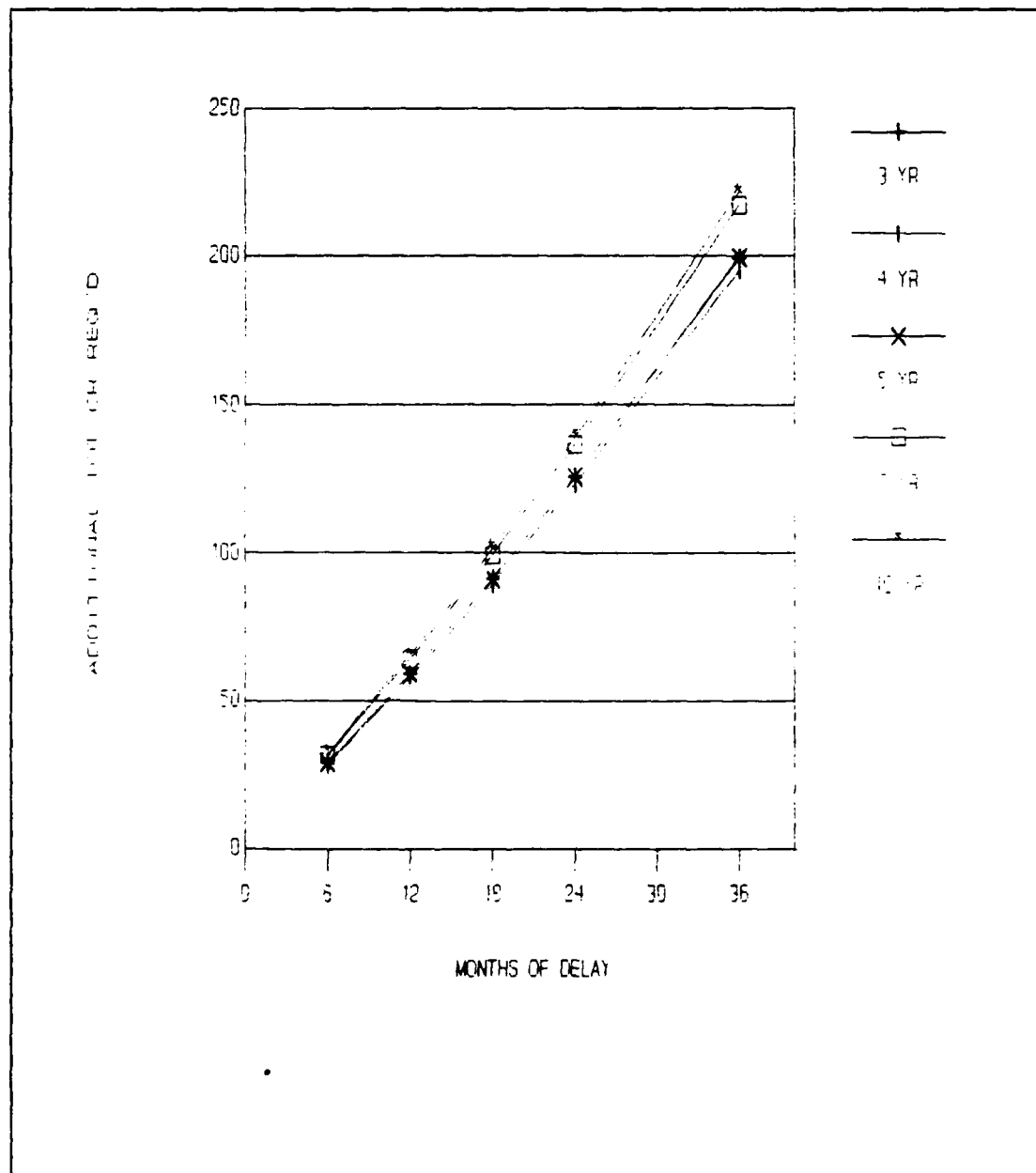


Figure 35. Additional Total Capital Recovery Required as a % of Upfront Cost Due to R&D Stretchout,  $i^*=12\%$ , 20-YR Operational Phase

# Appendix D. DSA Tables

Table 5. R&R Alternative

Nominal Value--386.22 million dollars

| <u>Variable</u>   | <u>High</u> | <u>Low</u> | <u>Delta</u> |
|-------------------|-------------|------------|--------------|
| R&D $\Delta$ CF   | 392.50      | 382.00     | 10.50        |
| R&D DLY           | 386.22      | 349.63     | 36.59        |
| $\Delta$ SAT COST | 455.45      | 351.66     | 103.79       |
| $\Delta$ LCH COST | 479.82      | 129.53     | 350.29       |
| R&D SCS           | 386.22      | -16.73     | 402.95       |
| R&D DECISION      | 386.22      | 0.00       | 386.22       |
| PROD DECISION     | 386.22      | -16.73     | 402.95       |

Table 6. S/R Alternative

Nominal Value--274.87 million dollars

| <u>Variable</u>   | <u>High</u> | <u>Low</u> | <u>Delta</u> |
|-------------------|-------------|------------|--------------|
| R&D $\Delta$ CF   | 281.14      | 268.59     | 12.55        |
| R&D DLY           | 274.87      | 248.00     | 26.87        |
| INFRA $\Delta$ CF | 280.20      | 269.53     | 10.67        |
| R&D SCS           | 274.87      | 9.25       | 265.62       |
| S/R MSN COST      | 305.54      | 244.19     | 61.35        |
| ORU COST          | 302.84      | 244.52     | 58.32        |
| $\Delta$ SAT COST | 302.30      | 247.44     | 54.86        |
| $\Delta$ LCH COST | 274.87      | 107.56     | 167.31       |
| $\Delta$ O&S COST | 283.66      | 263.87     | 19.79        |
| R&D DECISION      | 274.87      | 0.00       | 274.87       |
| PROD DECISION     | 274.87      | -3.63      | 265.62       |

# Appendix E. Probability Encoding Worksheets

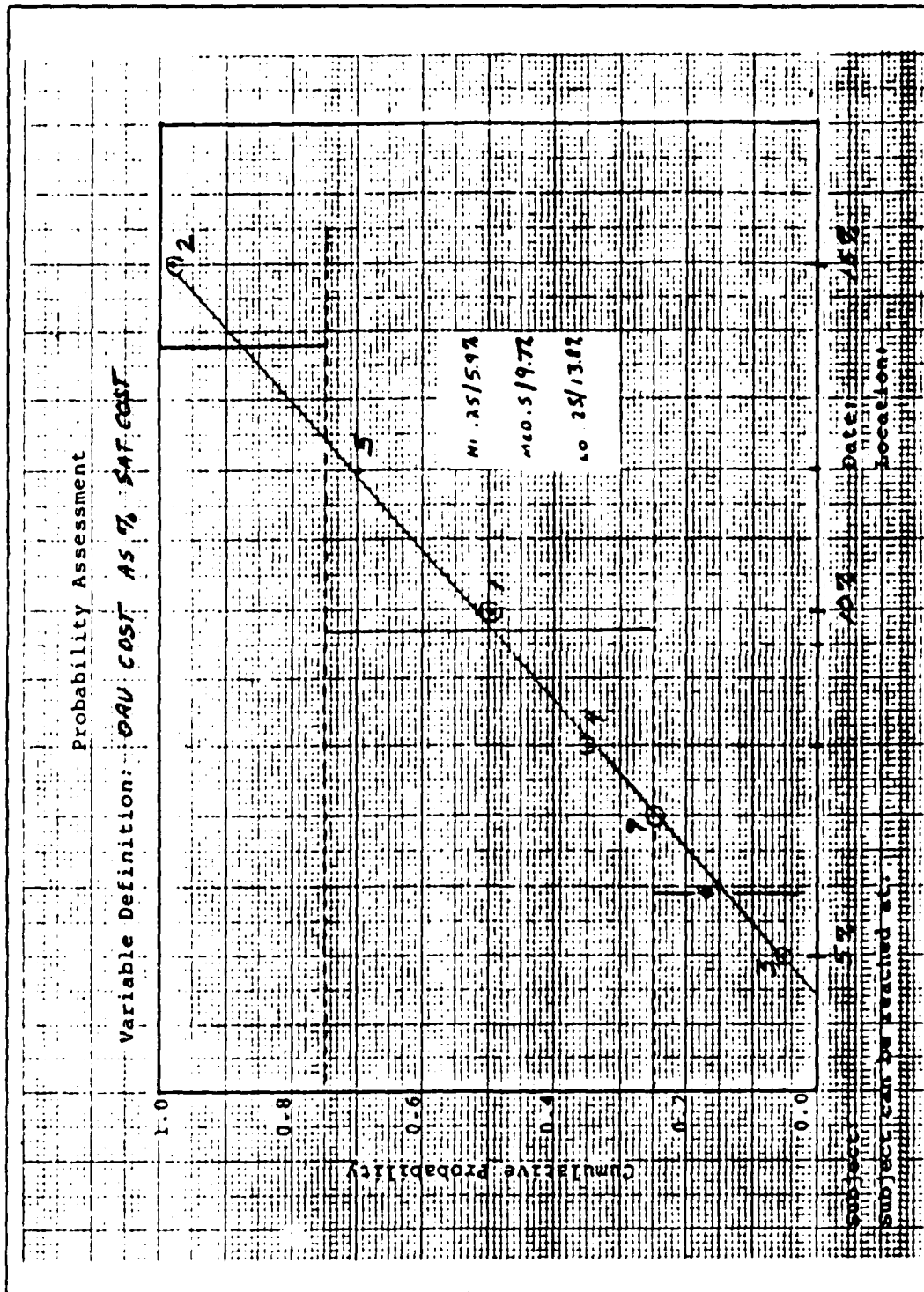


Figure 36. Probability Encoding Worksheet, ORU COST

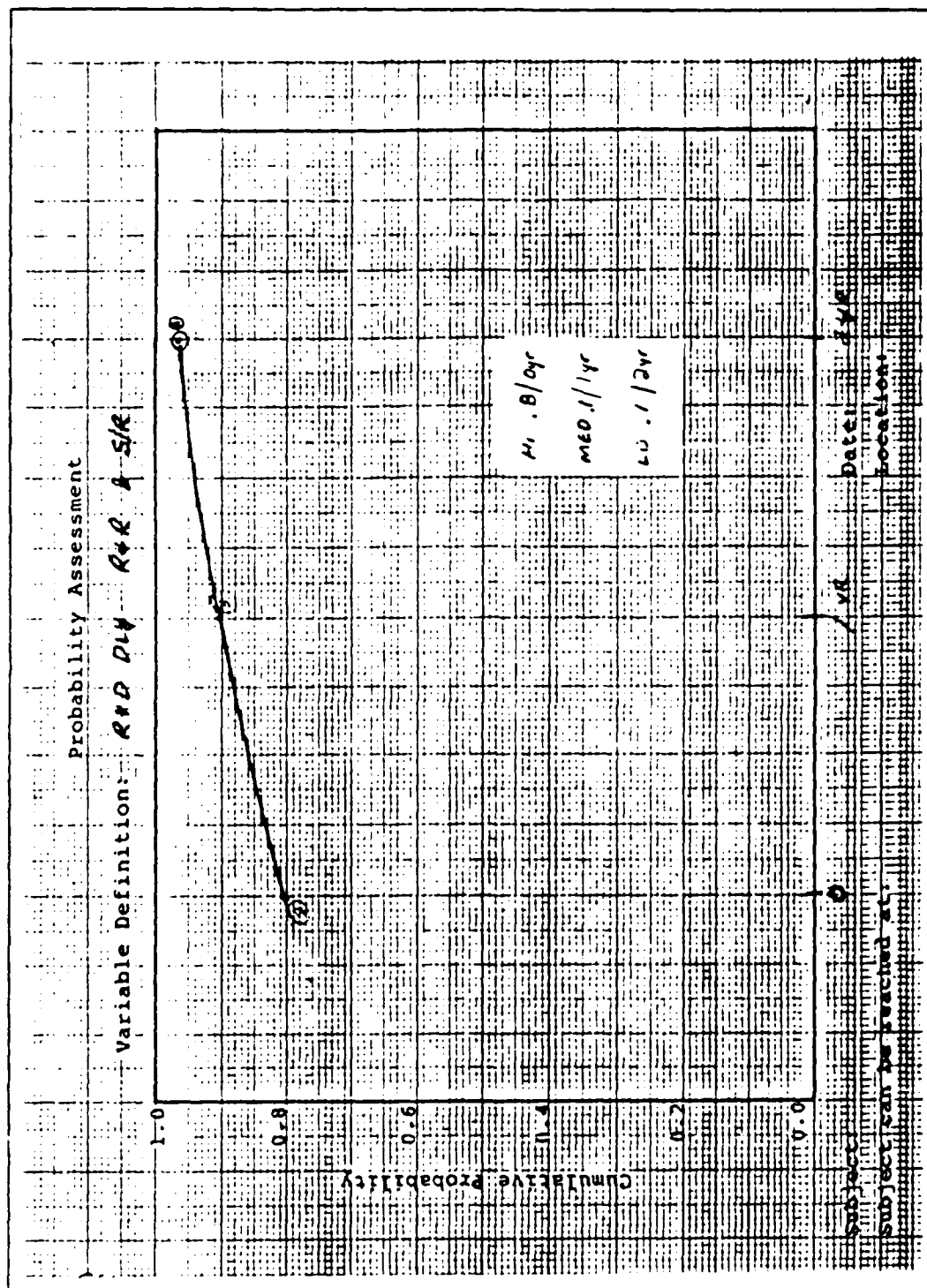


Figure 37. Probability Encoding Worksheet, R&D DLY



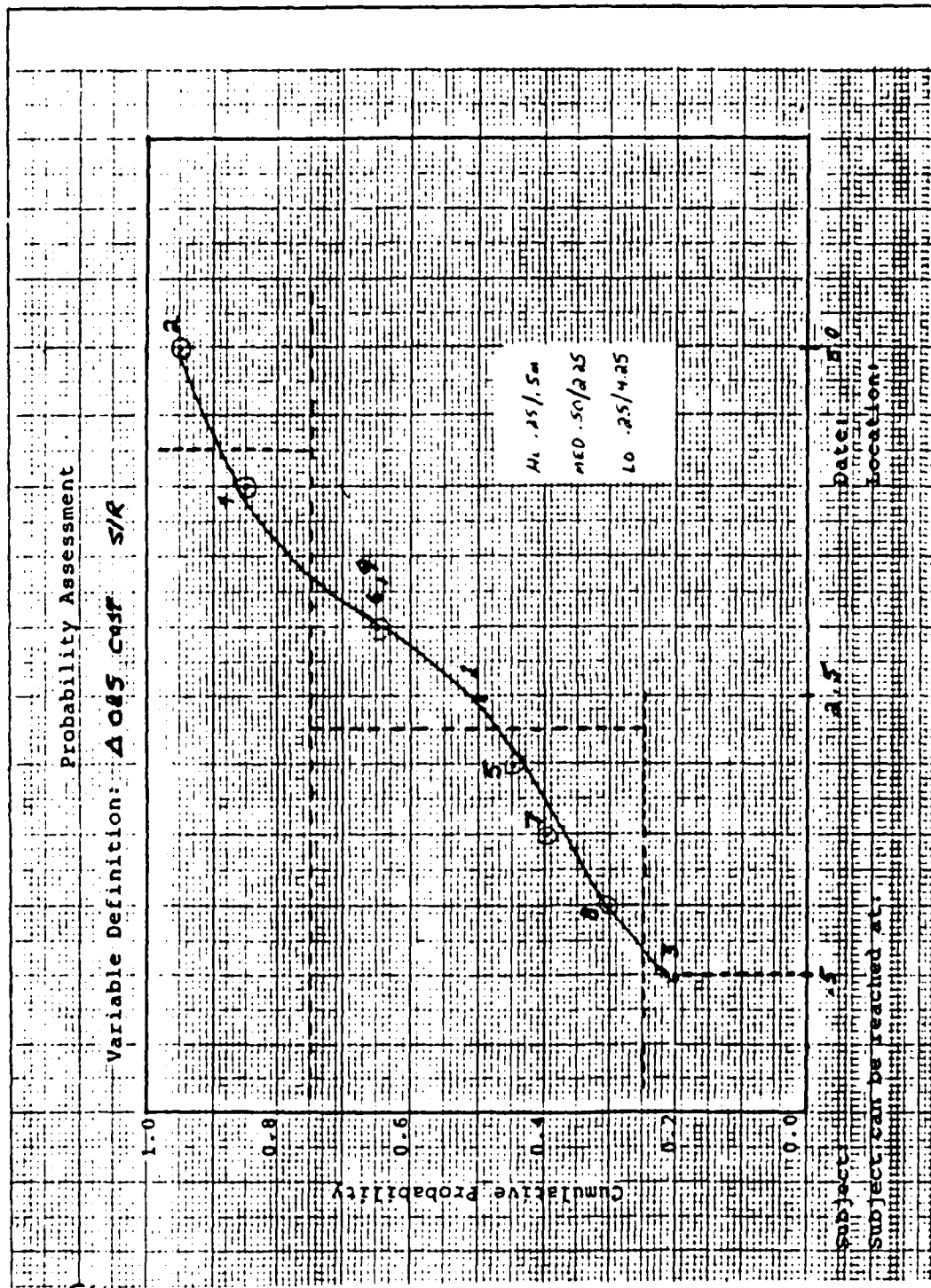


Figure 38. Probability Encoding Worksheet,  $\Delta O\&S$  COST

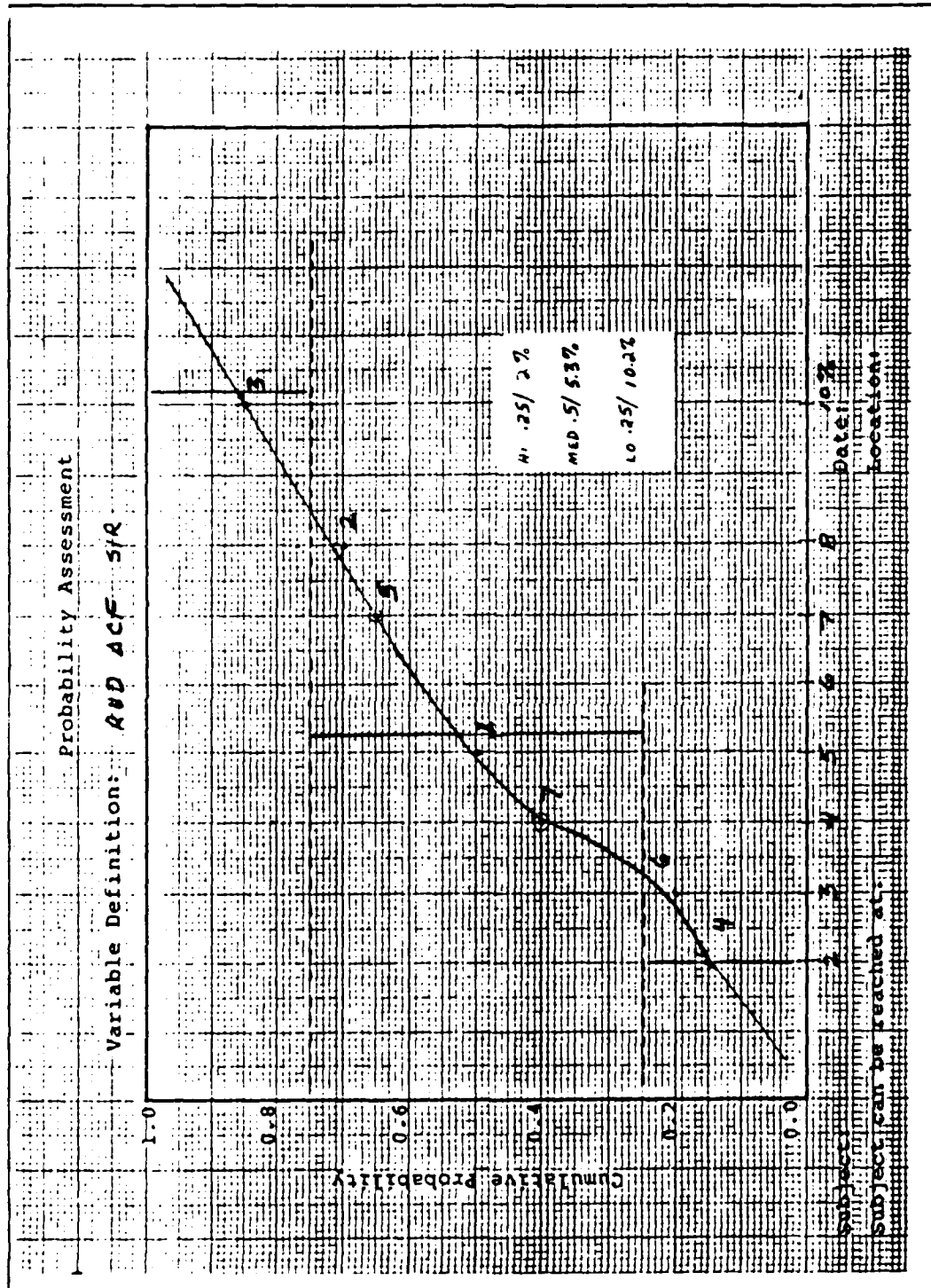


Figure 39. Probability Encoding Worksheet, S/R Alternative, R&D ACF

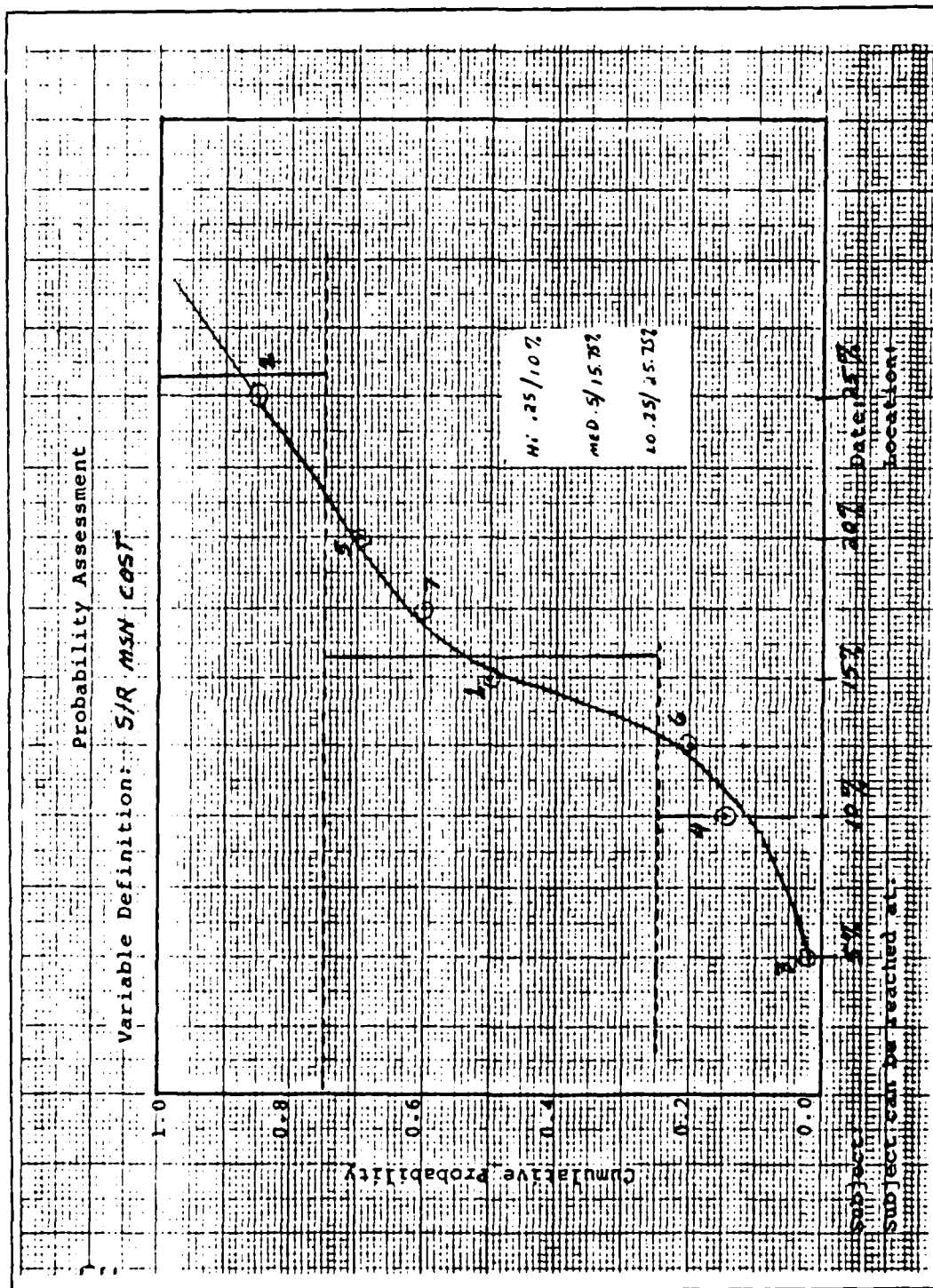


Figure 40. Probability Encoding Worksheet, S/R MSN COST

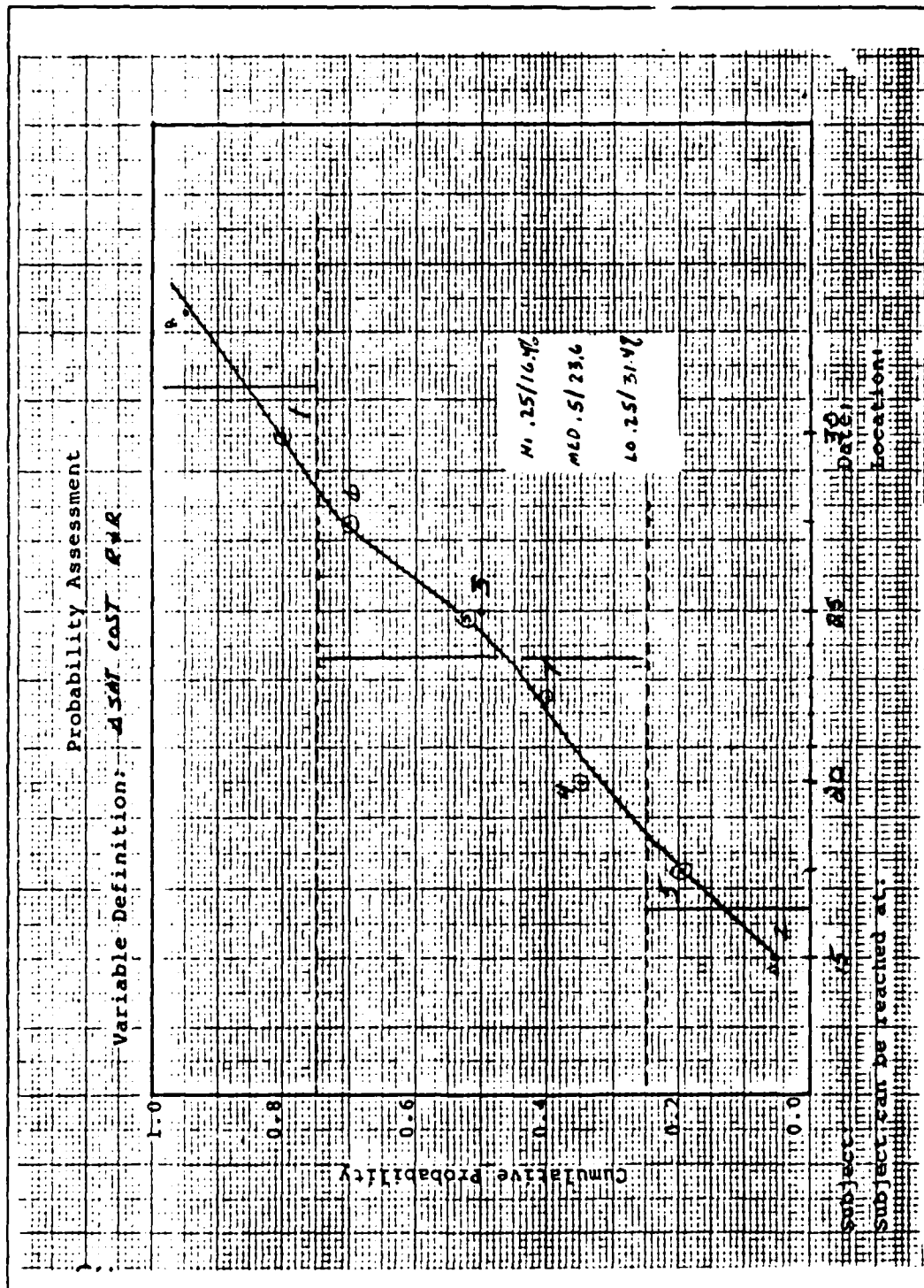


Figure 41. Probability Encoding Worksheet,  $\Delta SAT$  COST, R&R Alternative

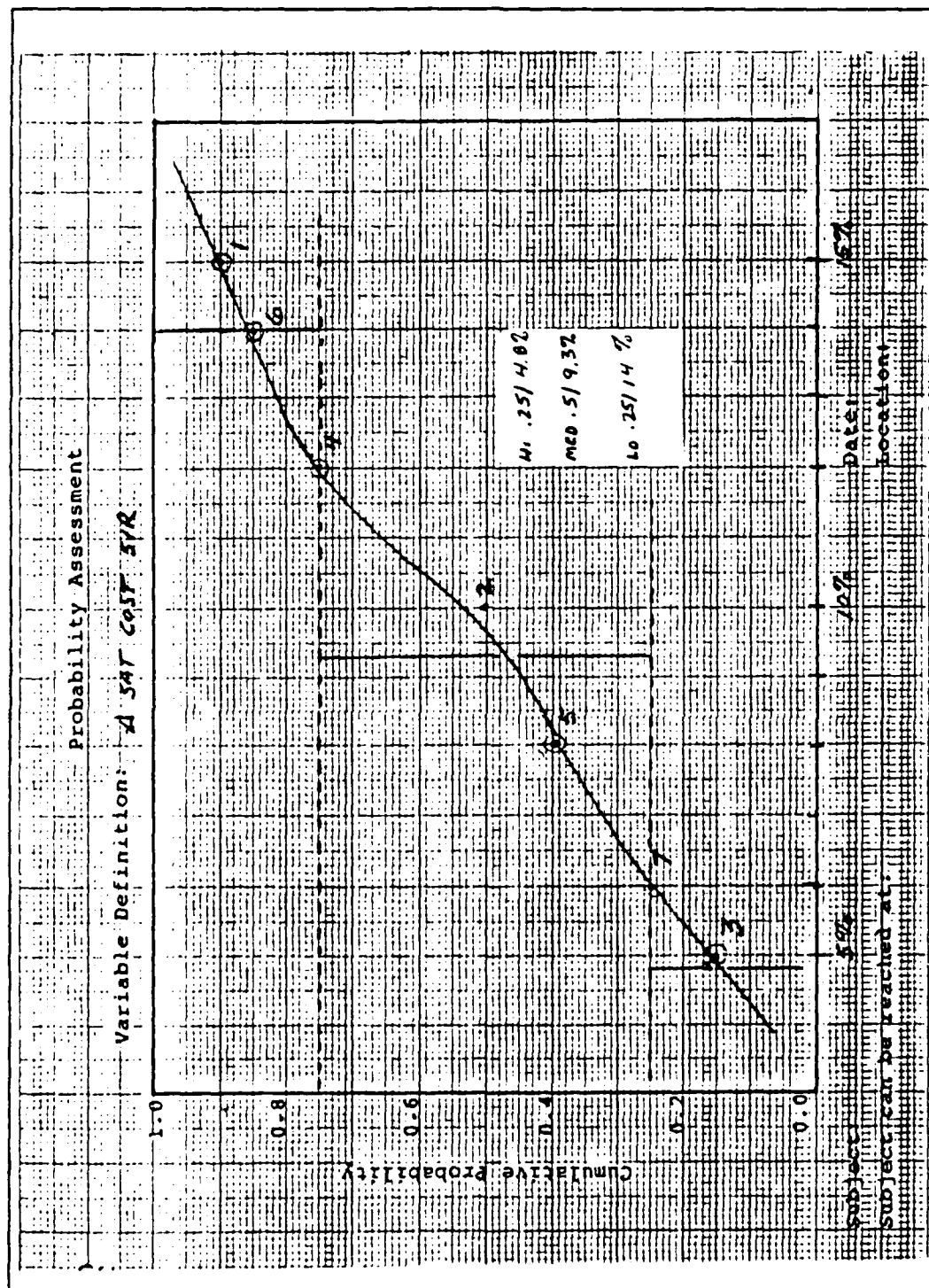


Figure 42. Probability Encoding Worksheet,  $\Delta$ SAT COST, S/R Alternative

## Glossary/Index

This is a glossary of abbreviations used and, when they are included, a page where they are further defined.

### Page/Definition

|  |    |
|--|----|
| CF--cash flow  |    |
| CR--capital recovery                                 |    |
| DA--decision analysis                                |    |
| DSA--deterministic sensitivity analysis              |    |
| DSCS--Defense Satellite Communications System        |    |
| ELV--expendable launch vehicle                       |    |
| EMU--extravehicular mobility unit. . . . .           | 7  |
| E(U)--expected utility                               |    |
| E(V)--expected value                                 |    |
| EVA--extravehicular activity . . . . .               | 7  |
| EVI--expected value of information . . . . .         | 73 |
| EVPI--expected value of perfect information. . . . . | 73 |
| EXP--expendable                                      |    |
| INFRA--infrastructure. . . . .                       | 19 |
| INTAN--intangible. . . . .                           | 29 |
| i*--discount rate. . . . .                           | 37 |
| LCH--launch  |    |
| LCH FAIL--launch failure . . . . .                   | 28 |
| L SCHED--launch schedule . . . . .                   | 21 |
| MMU--manned maneuvering unit . . . . .               | 7  |
| MSN--mission   |    |
| MSN SCS--mission success . . . . .                   | 28 |
| NPV--net present value                               |    |

|   | Page/Definition |
|---|-----------------|
| OMV--orbital maneuvering unit. . . . .  | 8               |
| OP LGTH--operational phase length. . . . .  | 19              |
| O&S--operations and support. . . . .  | 16              |
| ORBIT--orbital plane of a satellite. . . . .  | 21              |
| ORU--orbit replaceable unit   |                 |
| ORU COST--orbit replaceable unit cost. . . . .  | 23              |
| OTV--orbital transfer vehicle . . . . .   | 9               |
| PROD--production decision. . . . .  | 15              |
| P-V--probability-versus-value. . . . .  | 52              |
| R&D--research and development. . . . .  | 14              |
| R&D CF--the difference in R&D cash flow between an<br>alternative and expendable satellite program. . . | 17              |
| R&D DLY--delay, extension of the R&D phase . . . . .  | 22              |
| R&D RESULTS--results of the research and development phase  | 15              |
| R&D SCS--successful research and development . . . . .  | 21              |
| REC--recovery. . . . .  | 30              |
| RISK CF--risk cash flow. . . . .  | 28              |
| RMS--remote manipulator system . . . . .  | 6               |
| R&R--reliability and/or redundancy . . . . .  | 14              |
| RRR--retrieve, refurbish, relaunch . . . . .  | 14              |
| SAT--satellite  |                 |
| SAT FAIL--satellite failure. . . . .  | 28              |
| SAT LIFE--satellite design life. . . . .  | 21              |
| SLACK. . . . .  | 31              |
| S/R--service/repair. . . . .  | 15              |
| S/R MSN COST--service/repair mission cost. . . . .  | 23              |

|  | Page/Definition |
|--|-----------------|
| SURV-survivability . . . . .   | 29              |
| UPDATE . . . . .   | 29              |
| --delta, the difference. . . . .   | 16              |
| LCH COST--difference in launch cost between an alternative<br>and an expendable satellite. . . . .                             | 23              |
| O&S COST--difference in operations and support cost<br>between an alternative and an expendable<br>satellite program . . . . . | 23              |
| SAT COST--difference in satellite costs between an<br>alternative and an expendable satellite program . . . . .                | 23              |
| #SAT--number of satellites . . . . .   | 21              |



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ABSTRACT

→ The Air Force is considering adopting an on-orbit service/repair strategy for some of its satellites. The decision must be made on a program-by-program basis. A pilot decision analysis was conducted to demonstrate the application of the decision analysis methodology to the decision. A pilot model, using influence diagrams, was developed for a general satellite program. Several spreadsheet programs were constructed for use with the pilot model. A scenario was presented involving a hypothetical communications satellite program. The pilot model was applied to the program and an initial decision analysis was performed. The salient aspects of the analysis were presented to exhibit the advantages of decision analysis as a methodology for structuring and analyzing the decision. The example analysis revealed the strongpoints of the methodology when applied to the case of a decision maker faced with a decision involving uncertainty, complexity, and value preferences. The pilot model and analysis serve as a foundation upon which further application of the decision analysis technique to the on-orbit service/repair decision can build. Thesis. (SOL) *T*

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